PB80-180805

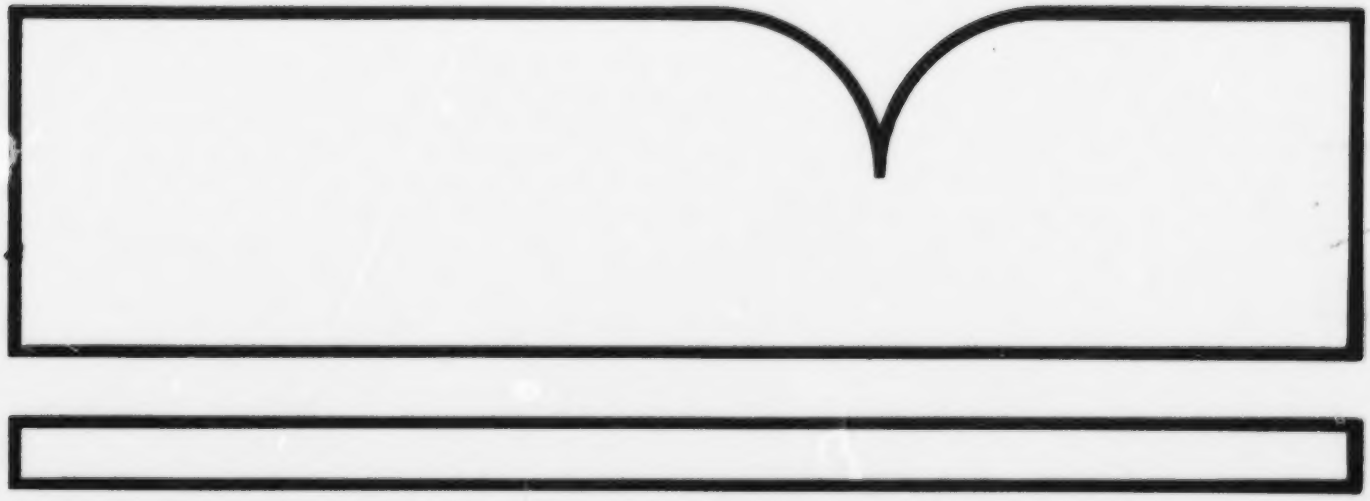
Winter Limnological Conditions in a Prairie Pothole Lake and the Application of Molecular Oxygen

South Dakota Cooperative Fishery Research Unit
Brookings

Prepared for

Office of Water Research and Technology
Washington, DC

Apr 79



U.S. Department of Commerce
National Technical Information Service
NTIS.

PB80-180805

Winter Limnological Conditions in a Prairie Pothole Lake and the Application of Molecular Oxygen

COMPLETION REPORT TO
WATER RESOURCES INSTITUTE
SOUTH DAKOTA STATE UNIVERSITY
PROJECT NO. A-069-SDAK
AGREEMENT NO. 14-34-0001-7069
APRIL 1979

BY
RICHARD A. PIKE
DIRECTED BY
RICHARD L. APPLEGATE
SOUTH DAKOTA
COOPERATIVE FISHERY RESEARCH UNIT
BROOKINGS, SOUTH DAKOTA

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC INFORMATION

PB80-180805

Winter Limnological Conditions in a Prairie Pothole Lake and the Application of Molecular Oxygen,

Apr 79

Richard A. Fike.

PERFORMER: South Dakota Cooperative Fishery Research Unit, Brookings.
Contract DI-14-34-0001-7088

SPONSOR: Office of Water Research and Technology, Washington, DC.
W8004812 OWRTA-059-SDAK(1)

Prepared in cooperation with South Dakota State Univ., Brookings. Water Resources Research Inst.

The use of molecular oxygen aeration under the ice cover as a method to prevent winterkill in Round Lake, South Dakota, was evaluated during the winter of 1977-1978. Physical, chemical and biological limnological conditions are documented for the period. Round Lake and other shallow eutrophic pothole lakes in South Dakota often suffer winterkill due to their high level of nutrients that promote rapid phytoplankton growth in summer. These phytoplankton die and decay rapidly consuming dissolved oxygen by catabolic processes in winter when the ice and snow cover prevents them from getting light. During the winter studied, the ice and snow cover was formed by December 20 and after that date phytoplankton numbers and chlorophyll concentration decreased.

KEYWORDS: *Aeration, *Limnology, *Lakes.

Available from the National Technical Information Service, Springfield, Va. 22161

PRICE CODE: PC A04/MF A01

ed Water
ources Abstracts
ut Transaction Form

1. Report No. I | 2. | 3. Accession No. W 80-04812

4. Title WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRE POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN,

5. Report Date
6.
8. Performing Organization Report No.

7. Author(s) Fike, R. A.

10. Project No. OWRT, A-059-SDAK (1)

9. Organization
South Dakota Cooperative Fishery Research Unit
Brookings, SD

11. Contract/Grant No.

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes
Completion Report ~~Agreement No~~ 14-34-0001-7088, April 1979.
~~Principal investigator~~ Applegate, R. L., principal investigator.
70 p, 14 fig, 5 tab, 32 ref.

16. Abstract
The use of molecular oxygen aeration under the ice cover as a method to prevent winterkill in Round Lake, South Dakota, was evaluated during the winter of 1977-1978. Physical, chemical and biological limnological conditions are documented for the period. Round Lake and other shallow eutrophic pothole lakes in South Dakota often suffer winterkill due to their high level of nutrients that promote rapid phytoplankton growth in summer. These phytoplankton die and decay rapidly consuming dissolved oxygen by catabolic processes in winter when the ice and snow cover prevents them from getting light. During the winter studied, the ice and snow cover was formed by December 20 and after that date phytoplankton numbers and chlorophyll concentration decreased. After January 19 dissolved oxygen declined to anoxic conditions and hydrogen sulfide gas levels peaked on February 12. Measurement of the community respiration by the diel oxygen method showed that it declined to a low on January 11 and 12 while water biochemical oxygen demand increased. A molecular oxygenation apparatus was used with three different strategies to release 711,400 liters of oxygen under the ice cover. While this oxygenation did have an effect on reversing the chemical and biological interactions leading to the lake's anoxic conditions, it was not successful in preventing winterkill. Calculations of total lake oxygen demand for the winter studied (which was severe) showed a demand of 1.05 x 10 to the 8th power liters of oxygen which would require an expenditure of $70,000 to $350,000 to prevent winterkill. (Seigler-IPA)

17a. Descriptors
*Oxygenation, *Limnology, *Winterkilling, *Iced lakes, South Dakota, Eutrophication, Lake stages, Phytoplankton, Biochemical oxygen demand, Metabolism, Hydrogen sulfide, Ice cover, Snow cover, Light penetration, Dissolved oxygen, Chlorophyll.

17c. COWRR Field & Group
02H

18. Availability Available from the National Technical Information Service, PB80 180805

19. Security Class. (Report)
20. Security Class. (Page)
21. No. of Pages 13
22. Price A02-P01

Send to:
Water Resources Scientific Information Center
OFFICE OF WATER RESEARCH AND TECHNOLOGY
U.S. DEPARTMENT OF THE INTERIOR
Washington, D.C. 20240

Abstractor S. Seigler | Institution Information Planning Associates, Inc.

WRSIC 102 (REV. OCTOBER 1977) GPO 922-911

COMPLETION REPORT

Project Number

A-059-SDAK

Agreement Number
14-34-0001-7088

WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

Principal Investigator

Richard L. Applegate

Graduate Research Assistant

Richard A. Fike

South Dakota Cooperative
Fishery Research Unit

Water Resources Institute
South Dakota State University
Brookings, South Dakota 57007

June, 1979

The work upon which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, U. S. Department of the Interior, Washington, D. C., as authorized by the Water Research and Development Act of 1978. The South Dakota Cooperative Fishery Research Unit (cooperators: South Dakota State University; South Dakota Department of Game, Fish and Parks; and U. S. Fish and Wildlife Service) provided equipment and laboratory facilities. Contents of this publication do not necessarily reflect the views and policies of the Office of Water Research and Technology, U. S. Department of the Interior, nor does mention trade names or commercial products constitute their endorsement or recommendation for use by the U. S. Government.

WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

BY

RICHARD A. FIKE

A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in Wildlife and
Fisheries Science (Fisheries Option),
South Dakota State University

1979

WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

Abstract

RICHARD A. FIKE

The physical, chemical, and biological conditions in Round Lake, Oakwood Lakes State Park, South Dakota were monitored during the 1977-1978 winter, and reaeration utilizing molecular oxygen was evaluated as a practical method to prevent winterkill.

Ice and snow conditions after 20 December, 1977 allowed little light penetration, and phytoplankton numbers (6174/ml to 1668/ml) and chlorophyll concentration (46.6 mg/L to 14.1 mg/L) decreased throughout the winter. Aquatic bacteria and fungi comprised from 87.0% to 93.7% by number of the total cells identified (phytoplankton, bacteria, and fungi) in the lake water under ice.

Dissolved oxygen declined to anoxic conditions after 19 January, 1978, and hydrogen sulfide gas reached a mean maximum (6.0 mg/L) on 12 February. Analysis of chemical parameters indicated increased chemical concentrations attributable to the "freezing out" of ions. A mean free carbon dioxide level increase from 0.95 mg/L to 59 mg/L was caused by increased respiration not counterbalanced by

photosynthesis.

Community respiration measured by the diel oxygen method (community metabolism) varied from 1.4 mg O_2/L/24 hrs 1-2 December, 1977, to a low (0.2 mg O_2/L/24 hrs) 11-12 January, 1978. Water biochemical oxygen demand (BOD) measurements from samples incubated below the ice indicated that mean lake BOD increased from 0.8 mg O_2/L/24 hrs 12 February, 1978, to 8.5 mg O_2/L/24 hrs 16 March, 1978. Sediment BOD was 10 to 15 times that of the water BOD during the same period.

Liquid oxygen stored in 127,440 L O_2 gas capacity tanks, rubber welders hose, and graphite air stones comprised the molecular oxygenation apparatus. Oxygenation employing 3 different strategies, resulted in 711,400 liters of oxygen gas being expended under the ice with few positive effects noted in reducing anoxic conditions in the lake.

The total lake oxygen demand for the 4 month period was calculated to be 1.05×10^8 L O_2. Depending on molecular oxygen dissolution efficiency, an expenditure of $70,000 to $350,000 for oxygen alone, might have been required to prevent winterkill in Round Lake during 1977-1978.

ACKNOWLEDGMENTS

I sincerely appreciate the guidance and suggestions of Dr. Richard Applegate during the study and in preparation of the manuscript. I also wish to thank Dr. Donald C. Hales for his suggestions during the first year of the field work and Dr. Charles G. Scalet, Dr. Robert S. Benda, Dr. Lois Haertel, and Dr. Charles L. Lay for their suggestions and helpful criticisms in preparing the manuscript. Dr. Paul R. Middaugh provided valuable assistance in the identification of the aquatic bacteria and fungi.

My earnest thanks to Thomas D. Gammon, John M. Kelly, David B. Hogue, and Wayne L. Kruckenberg for help in the laboratory and field work. A special note of appreciation is also due the Oakwood Lakes State Park staff for their cooperation and assistance during field work.

Financial support, equipment, vehicles, and supplies were provided by the South Dakota Water Resources Institute and the South Dakota Cooperative Fishery Unit[1].

RAF

[1]Cooperating agencies: South Dakota Department of Game, Fish and Parks, South Dakota State University, and United States Fish and Wildlife Service.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
STUDY AREA	5
MATERIALS AND METHODS	10
Oxygenation Experiment 1	18
Oxygenation Experiment 2	20
Oxygenation Experiment 3	20
RESULTS AND DISCUSSION	22
Physical Conditions	22
Chemical Analysis	22
Biological Interactions	31
Oxygenation Experiment 1	48
Oxygenation Experiment 2	49
Oxygenation Experiment 3	50
Cost-Benefit Discussion	56
LITERATURE CITED	59

LIST OF FIGURES

Figure		Page
1.	Winterkilled fish piled along the shore of East Oakwood Lake at a spring area during breakup of the ice, March, 1978	3
2.	Map of Oakwood Lakes State Park, Brookings Co., South Dakota showing the location of Round Lake	6
3.	Contour map of Round Lake, Oakwood Lakes State Park, Brookings Co., South Dakota, 1977	8
4.	Above left: Gas Pack 45 oxygen tank with regulator and hoses. Above right: Graphite air stone. Below: Open water above the oxygenation site at termination of oxygenation	17
5.	Placement of the air stones and sampling sites. Above: Oxygenation experiments 1 and 2. Below: Oxygenation experiment 3	19
6.	Profile of Round Lake on a NW to SE axis showing water temperature (C) and ice cover on selected dates, winter of 1977-1978	24
7.	Comparison of mean specific conductance, dissolved solids, and total hardness concentrations in Round Lake during the winter of 1977-1978	27
8.	Comparison of mean HCO_3 alkalinity, free CO_2, and pH in Round Lake during the winter of 1977-1978	28
9.	Comparison of mean dissolved oxygen and hydrogen sulfide levels in Round Lake during the winter of 1977-1978	30
10.	Mean lake community metabolism by date in Round Lake, winter, 1977-1978	32-33
11.	Total community respiration at each station on Round Lake by the community metabolism method	36

Figure Page

12. 24 hour lake water BOD by date at selected stations on Round Lake, winter, 1977-1978 . 37-38

13. 24 hour sediment BOD in Round Lake, winter, 1977-1978. Above: Station 5B by date. Below: Stations 1, 2, and 3 by date 43

14. Plankton percent composition by number of cells, colonies, or filaments, and total cells (no./ml). Miscellaneous genera comprising less than 1% of the population were: Agmenellum, Scenedesmus, Kirchneriella, Actinastrum, Glenodinium, Cryptomonas, Stichosiphon, Micractinium, Melosira, Phacus, Tetraedron, Schroederia, Navicula, and Golenkinia 45

LIST OF TABLES

Table		Page
1.	Ice and snow conditions and secchi disk visibility on Round Lake during the winter of 1977-1978	23
2.	Mean chemical analysis of Round Lake during the winter of 1977-1978 including the corresponding 95% confidence interval	26
3.	Mean chlorophyll and plant carotenoid levels in Round Lake during the 1977-1978 winter . .	47
4.	Chemical analysis comparing stations on Round Lake, March 15, 1978	54
5.	Chemical analysis comparing stations on Round Lake, March 14, 1978	55

INTRODUCTION

The objectives of this study were to document winter limnological conditions in highly eutrophic Round Lake, Oakwood Lakes State Park, South Dakota during the winter of 1977-1978, and evaluate molecular oxygen aeration under ice cover as a practical method to prevent winterkill.

The northeastern South Dakota glacial lakes district abounds in shallow eutrophic pothole lakes. Eutrophication is a result of natural or artificial nutrient additions to a body of water (National Academy of Sciences 1969).

Fertilizer and sediment run-off from agricultural land is the largest problem contributing to water pollution in South Dakota. Pollutants deposited on lake bottoms over a period of years may become a longlasting source of enrichment. An example of this is the Oakwood Lakes near Bruce, South Dakota. The South Dakota Department of Environmental Protection (1978) reports that the major water quality problems in the Oakwood Lakes are high nutrient and unionized ammonia concentrations.

Winters in the northern prairie states are characteristically severe. Ice and snow cover usually lasts from November through March with ice reaching thicknesses up to 100 cm and snow 30 to 40 cm or more. When ice and snow cover prevents sufficient light from reaching the phytoplankton in eutrophic lakes, they die and decay rapidly. Consumption

of dissolved oxygen by catabolic processes can then exceed augmentation by photosynthesis, and lead to severe reductions in dissolved oxygen or even to total anoxia (Wetzel, 1975). This phenomenon is termed "winterkill", and has detrimental effects on aquatic life.

Oakwood Lakes State Park has a history of winterkills documented as far back as 1951-1952, and has suffered at least a partial winterkill the last 3 winters (1976-1979), (South Dakota Department of Game, Fish, and Parks, lake survey data, 1951-1979, unpublished). The scope of the winterkill problem was demonstrated by the extensive winterkill of 1977-1978 (Fig. 1). The majority of northeastern South Dakota lakes, including Lake Poinsett, the largest natural lake in the state, were affected.

The investigation of molecular oxygen use in reaeration is relatively recent. Since oxygen comprises approximately 19% of the atmosphere, molecular oxygen has a solubility in water approximately five times greater than compressed air. Therefore smaller amounts of molecular oxygen would be required for reaeration. However, the oxygen must be manufactured and the advantage of less quantity may be offset by the disadvantage of higher cost (King 1970, and LaBounty and King 1977). Speece (1969, 1971) found that pure oxygen often was economically competitive for artificial aeration. Proper oxygenation system design can make

Fig. 1. Winterkilled fish piled along the shore of East Oakwood Lake at a spring area during breakup of the ice, March, 1978.

molecular oxygen use efficient and advantageous. Various studies have investigated optimum oxygenation system design and methodology with molecular oxygen (Amberg et al. 1969; Speece 1969, 1971; King 1970; Fast et al. 1975; LaBounty and King 1977; Lorenzen and Fast 1977).

There is a paucity of research related to molecular oxygen use under winter ice cover. Seppänen (1974, cited by Lorenzen and Fast 1977) described the design and operation of a liquid oxygen aerator on lakes Hemtrask and Kiteenjarni, Finland during winter ice cover. LaBounty and King (1977) researched a technique utilizing liquid oxygen to prevent winter anoxia with positive results. Molecular oxygen gas produced from liquid oxygen passed through tubing and a series of diffusers mounted approximately 20 meters below the ice and 1 meter above the bottom.

STUDY AREA

Round Lake is situated in Oakwood Lakes State Park, 4.8 kilometers west of Bruce, South Dakota, in northwestern Brookings County. It is the smallest (21 ha) lake of a group of 5 within the park (Fig. 2). These lakes are glacial in origin and lie on the Coteau des Prairies, a highland area between the Minnesota-Red River lowland and the James River lowland in eastern South Dakota.

The Oakwood Lakes are high in dissolved solids and exist as a closed system except for runoff and ground water seepage. Many sloughs and potholes are in the area. Inflow and drainage streams are small with intermittent flow. Round Lake is connected at its west side to West Oakwood Lake (Tetonkaha Lake) during highwater levels. Prior to this study South Dakota had experienced a drought period, and although 1977-1978 was a period of normal moisture levels, the lakes still had not returned to normal levels.

The watershed surrounding the Oakwood Lakes area is agricultural with several farming and feedlot operations extending to the lake edges on the park boundaries. Summer cabins and a resort area line the southern shore of West Oakwood Lake. Round Lake lies entirely within the park, with no development on its shores except for a park roadway along the south and east sides.

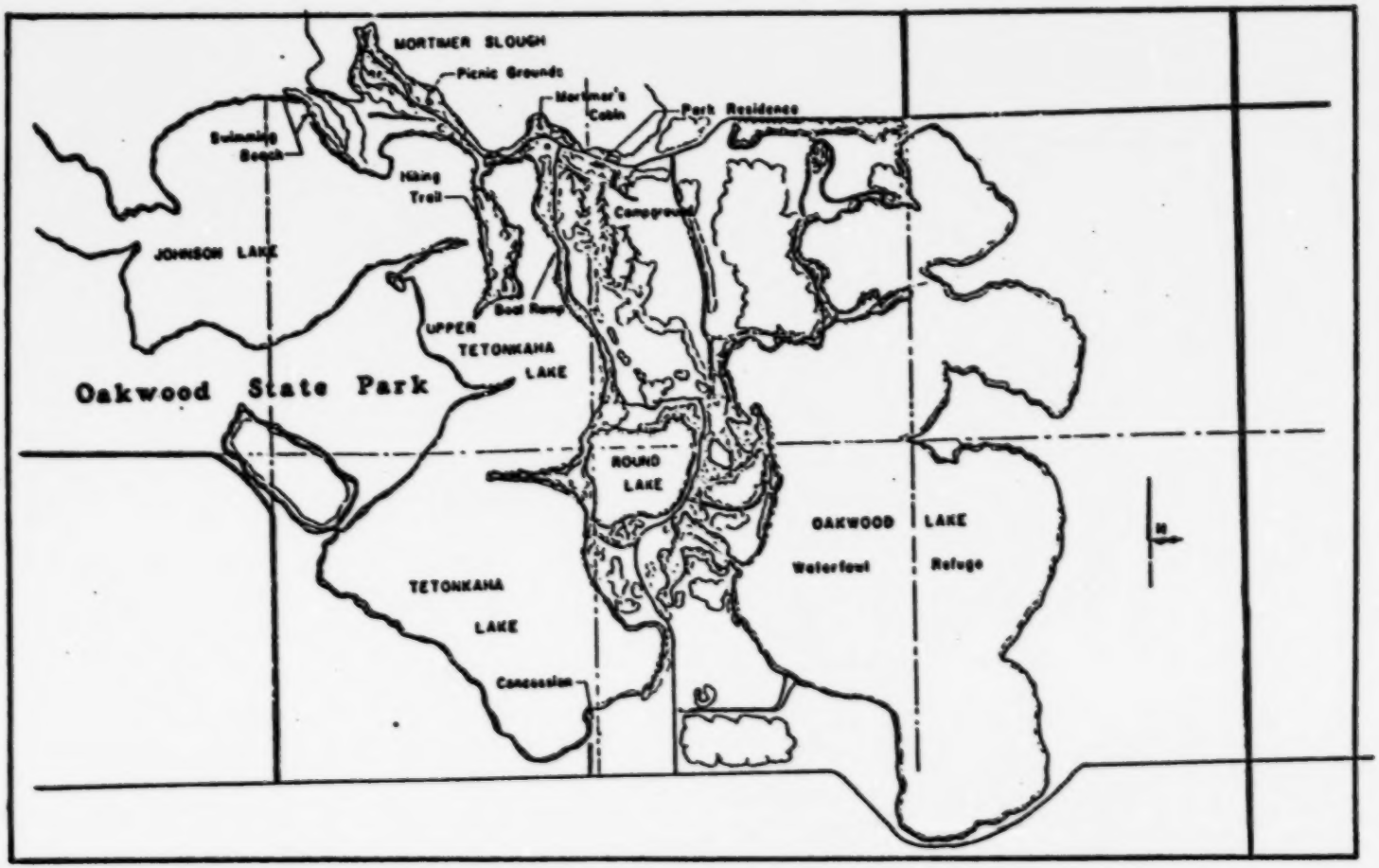


Fig. 2, Map of Oakwood Lakes State Park, Brookings Co., South Dakota, showing the location of Round Lake.

The Oakwood Lakes are all relatively shallow and flat bottomed with maximum depths of 3.0 m in East and West Oakwood Lakes and 1.4 m in Round Lake during the study period (Fig.3).

Blue green algal blooms occur during the summer and fall periods. The water is characteristically greenish brown in color. The lake bottoms are heavily silted with fine grained, organically rich mud. Shorelines subjected to wave action vary from sand and gravel to rubble and boulders. Submerged and emergent vascular aquatic vegetation is limited in the lakes to a few scattered areas due to shifting substrate, limited light penetration, and carp, Cyprinus carpio, activity.

The Oakwood Lakes have historically supported a high density of black bullheads, Ictalurus melas. Prior to 1968 during winterkill free periods, high densities of yellow perch, Perca flavescens, and walleye, Stizostedion vitreum, flourished in the lakes (South Dakota Department of Game, Fish, and Parks, lake survey data, 1951-1979, unpublished). A severe winterkill during 1968-1969 decimated the sport fish population. The lakes have since been stocked with northern pike, Esox lucius, (considered to be more tolerant of lower oxygen conditions), and adult yellow perch. The forage fish population consists primarily of carp, fathead minnows, Pimephales promelas, white suckers,

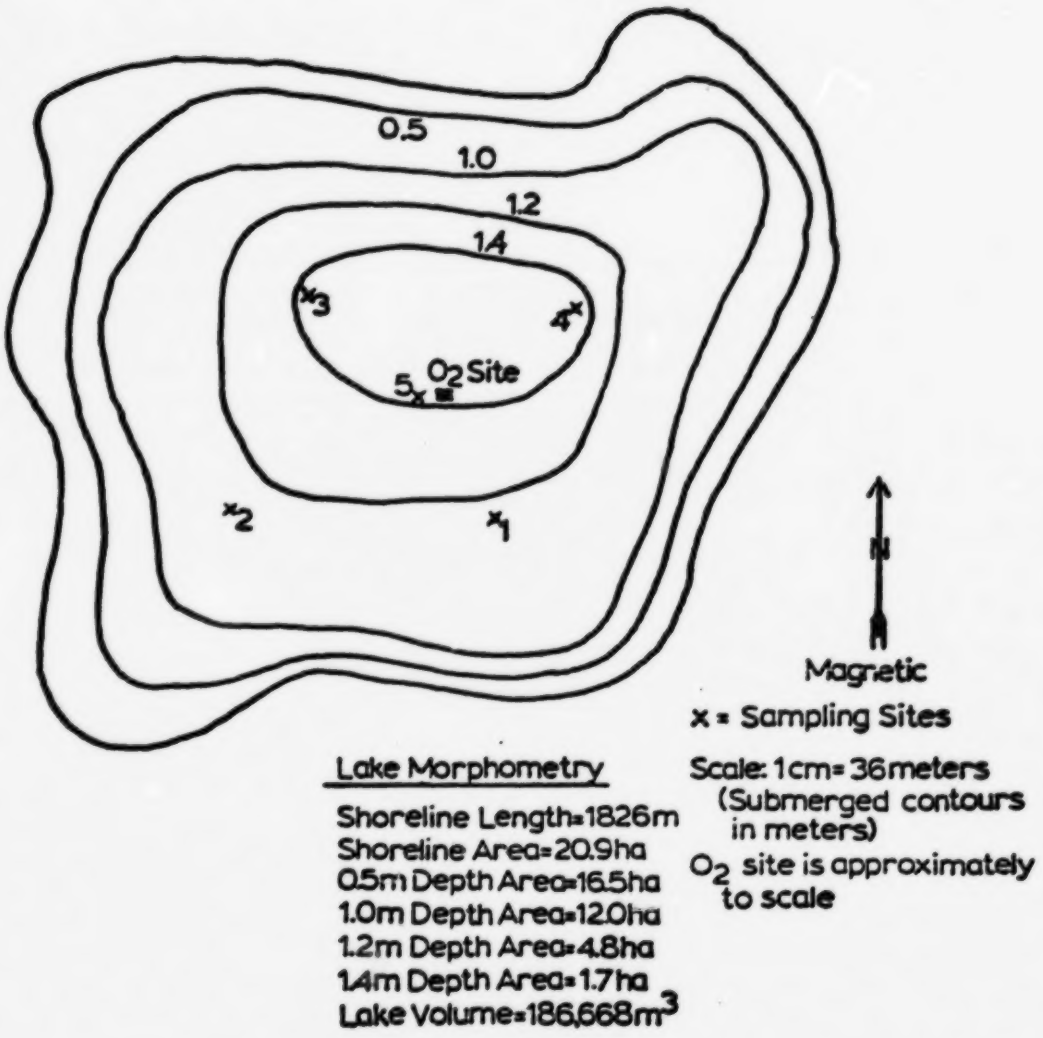


Fig. 3. Contour map of Round Lake, Oakwood Lakes State Park, Brookings Co., South Dakota, 1977.

Catostomus commersoni, and bigmouth buffalo, Ictiobus cyprinellus.

MATERIALS AND METHODS

Measurements were first taken December 1, 1977, on the lake to determine physical characteristics. Water depth was measured through the ice. The lake was mapped to scale using the outline from a 1964 South Dakota Department of Game, Fish, and Parks map, and the volume calculated. Water stages in both 1964 and 1977 were similar. Five permanent sampling stations were established, marked, and the oxygenation site located (Fig. 3).

On each sampling date ice thickness was measured at each station and a relative observation made of ice clarity, snow condition, and percentage snow cover on the lake. The depth of deepest snow cover was measured with a meter stick and recorded. Weather conditions, time of day, and other general observations were also recorded. All samples were taken one to two hours before sunset. Light penetration was measured with a secchi disk lowered into a hole drilled through the ice. Battery failure due to cold temperatures, prevented the use of a relative irradiance meter with a submersable photocell.

Water sample collection in subfreezing weather often required specialized techniques. Glass BOD bottles were subject to rapid freezing and shattering. The solution was to place the filled sample bottles in an ice chest warmed with hot water bottles. After the chest was

transported to the vehicle, the first two Winkler reagents were added. Any error incurred in dissolved oxygen measurement by this technique was unavoidable and constant throughout the sampling period.

Similar problems in collection of water samples for other parameters were nullified by the use of 4 L plastic sample bottles. Problems with the use of any battery powered instrument were related to battery power loss due to the cold, or freezing of electrodes. Any analysis requiring the use of a battery powered instrument was completed in the vehicle or laboratory. The only exception was water temperature, with the sole solution being rapid measurement. All sample collection and measurements on the ice were conducted with the aid of a snowmobile.

All water samples were analyzed according to procedures outlined in the American Public Health Association (1971) unless otherwise indicated. Water samples were collected with a 2 L (PVC) plastic Kemmerer water sampler and stored in 4 L plastic water bottles (filled to the top to avoid aeration), for transportation to the laboratory. Care was taken to avoid agitating the water while drilling holes in the ice and sampling. Due to the shallow nature of the lake and the ice thickness, only temperature was measured at different depths. Samples were taken at a mean point between the ice and bottom sediment. Three replicate

samples were taken and reported as a mean value.

Water temperature was measured just below the ice and at 0.5 intervals using a battery powered Yellow Springs Instruments Company resistance thermometer. Specific conductance was measured in the laboratory at 25 C using a platinum electrode, temperature compensating conductivity meter. Dissolved solids samples were filtered through 0.45um pore size, acid washed Millipore filters. Three 50 ml portions of the filtrate were dried at 179-181 C overnight, then placed in a desiccator until weighed. Samples for the determination of pH were collected in 300 ml BOD bottles to prevent CO_2 loss from the sample, placed in an ice chest with hot water bottles to prevent freezing, and transported to the vehicle. The pH determination was made immediately in the vehicle using a temperature compensating, portable pH meter with polyethylene covered glass electrode. The meter was calibrated daily with standard buffer solutions prepared by the Hach Chemical Company. Free CO_2 was determined using the nomographic method. Phenolphthalein alkalinity and total hardness were analyzed in the laboratory. Total alkalinity and total hardness were analyzed in the laboratory. Total alkalinity was measured by the mixed bromcresol green-methyl red indicator method and the appropriate calculations made to obtain the CO_3 and HCO_3 fractions. Hydrogen sulfide was determined in the field

by use of a Hach Chemical Company test kit from samples collected in 300 ml BOD bottles. Samples for dissolved oxygen determination were collected in 300 ml BOD bottles, placed in an ice chest with hot water bottles, and transported to the vehicle. They were then immediately fixed using the azide modification of the Winkler method. The fixed samples were acidified and titrated in the laboratory.

To measure the community production and respiration of oxygen, the diel oxygen method (community metabolism) developed by McConnel (1962) was selected. This method allowed the calculation of gross photosynthesis and community respiration. The ratio of photosynthesis to respiration furnished an indicator by which the progression to winterkill could be plotted. In addition, phytoplankton and bacterial cell counts were made. Three lake water samples were collected from each station and pooled into 4 L plastic bottles. Three 500 ml samples were measured from each mixed sample bottle and concentrated to 10 ml using an ultracentrifuge. The concentrated samples were preserved with Lugol's solution. Cell counts were made using the Edmundson technique (Lackey 1938). A 0.1 ml sample was pipetted onto the counting slide and the 100 most abundant cells, colonies, or filaments counted at 400 x. Phytoplankton was identified to genus according to Prescott

(1962, 1970). The aquatic bacteria and fungi (those visible at 400 x) were identified according to Cooke (1963) and Prevot (1966).

Spectrophotometric determinations of chlorophylls and plant carotenoids were made on Round Lake water according to the methodology in Strickland and Parsons (1968). Sample collection was the same as previously described for cell counts. A Bausch and Lomb Spectronic 70 spectrophotometer and 1 cm light path cuvettes were used to measure the sample light extinction (absorbance).

When it was no longer possible to measure dissolved oxygen, it was necessary to abandon the community metabolism procedure and measure respiration by the BOD method (American Public Health Association 1971). Samples of lake water were collected in 4 L plastic bottles and saturated with air by shaking them. Four 300 ml BOD bottles were filled and overflowed several times their volume by siphoning the aerated water from the plastic bottles. Three bottles were incubated under the ice for 24 hours. The first 2 Winkler reagents were added to the fourth bottle to provide a measure of the initial oxygen concentration in the bottles. After 1 March, 1978, the lake water was diluted with standard dilution water before filling the BOD bottles. Dilutions up to a factor of 0.8 were required. Concurrently a BOD determination

was made on the lake bottom sediment. A sediment sample to a 5 cm depth, was obtained with an Ekman dredge. The sediment was mixed in a bucket to obtain a homogeneous sample and a portion diluted with aerated standard dilution water to a factor of 0.99. The mixture was siphoned into 4 500 ml BOD bottles. Three were incubated under the ice for 24 hours. The fourth was flocculated to remove sediment interference with the Winkler dissolved oxygen determination. Then the first two Winkler reagents were added to measure the initial oxygen level. All bottles were treated using the alum-flocculation modification of the Winkler method.

The sediment volume affecting the lake water oxygen demand was calculated using the lake surface area and a 5 cm depth. The lake volume was calculated from measurements taken just after ice cover occurred, then corrected for ice cover throughout the winter. Ice volume was calculated using the lake surface area divided by the coefficient of expansion for ice (1.125).

Mean sediment and water oxygen demand values from community respiration and BOD (water and sediment) measurements throughout the winter were multiplied by the associated sediment volume and lake volume respectively during that period then combined. These short time period totals were then combined to obtain total lake oxygen

demand over the 4 month period from December through March. The amount of molecular oxygen required to increase the dissolved oxygen in the water to 5 mg/l was also calculated. This level is usually considered as the minimum acceptable dissolved oxygen level to sustain most sport fish. Whenever community respiration or BOD measurements were taken, such as the sediment BOD values during the first part of the study, the closest measurement time wise was used in the short time period oxygen demand calculation.

Prior to the initiation of sampling, the molecular oxygenation apparatus was tested in the laboratory. All materials were obtained from the Dakota Welding Supply Company, Sioux Falls, South Dakota. The graphite oxygenation stones, through which molecular oxygen was bubbled into the water (Fig. 4), were obtained from the Union Carbide Corporation, Chicago, Illinois. These stones measured 1.9 m in length with a 5.1 cm diameter. The air stone's center was hollow to a diameter of 1.3 cm permitting gas passage the stone's length. The stones were modified with 1.4 cm diameter welder's hose fittings on one end and threaded plugs on the other. A desirable characteristic of the graphite stone was the extremely small diameter bubbles released, facilitating more efficient molecular oxygen dissolution. A 1.4 cm diameter welder's hose connected each graphite stone to the regulator and

Fig. 4. Above left: Gas Pack 45 oxygen tank with regulator and hoses. Above right: Graphite air stone. Below: Open water above the oxygenation site at termination of oxygenation.

oxygen tank (Fig. 4). The Gas Pack 45 oxygen tank had a 127,440 L molecular oxygen gas capacity at atmospheric pressure. A smaller K tank, used when it was necessary to recharge the Gas Pack 45, had a 6910 L capacity. At a 15 L/min. maximum flow rate, each Gas Pack 45 oxygen tank had sufficient capacity to last approximately 6 days.

The oxygenation site was located near the lake center within the deepest contour (Fig. 3). Sampling sites were selected to allow measurement of dissolved oxygen dispersal (Fig. 5). During oxygenation experiments 1 and 2, the air stones were suspended 10 cm off the bottom with ropes anchored in the ice to prevent sediment mixing. The stones were moved for oxygenation experiment 3. It was not possible to resuspend the stones from the ice due to ice thickness, and they rested on the bottom.

Oxygenation Experiment 1

On 14 January, 1978 the mean dissolved oxygen level on Round Lake was decreasing rapidly. Molecular oxygen gas at a 5 L/min. rate was released under the ice for 4 hours. Dissolved oxygen determinations were made before, immediately following, and 24 hours after oxygenation at sampling sites within the oxygenation area. When oxygenation ceased, the stones and hoses were removed from the water to prevent freezing.

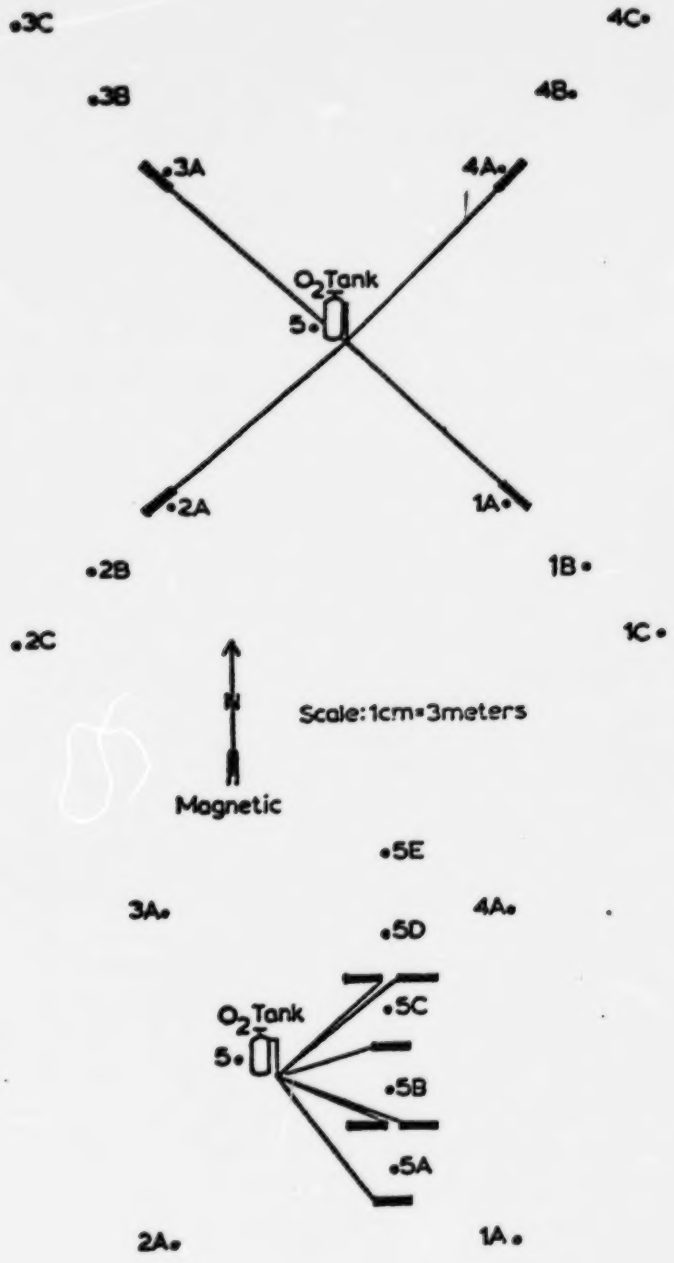


Fig. 5. Placement of the air stones and sampling sites. Above: Oxygenation experiments 1 and 2. Below: Oxygenation experiment 3.

Oxygenation Experiment 2

Between 21 and 23 January, 1978 molecular oxygen gas was released at a 10 L/min. rate for 48 hours. Dissolved oxygen determinations were made before, after 24 hours, and at completion of oxygenation. Test netting was conducted under the ice during oxygenation using a 30.5 m, 0.6 to 3.8 cm variable mesh experimental gill net to determine if fish were being attracted to the area. The stones and hoses were removed after oxygenation ceased.

Oxygenation Experiment 3

After experiments 1 and 2, the oxygenation stones were placed closer together under the ice to provide a concentrated oxygenation area. Between 1 February and 14 March, 1978, oxygen gas was released under the ice continuously for 42 days (1008 hrs.) at the maximum 15 L/min. rate. To prevent emptying the tank completely and to provide a continuous oxygen gas flow, at 5 day intervals the Gas Pack 45 oxygen tank was replaced by a smaller K tank and recharged. Due to the smaller K tank capacity, molecular oxygen flow under the ice was reduced to 3 to 4 L/min. until the Gas Pack 45 oxygen tank could be recharged and reconnected. Dissolved oxygen determinations were made in the oxygenation site at 3 day intervals.

In an attempt to determine the oxygenation effects other than dissolved oxygen measurements, comparisons

were made utilizing various parameters measured in and outside (sampling sites 1-4) the oxygenation site, both during and after the oxygenation. These included; BOD in the lake water and sediment, water temperature, secchi disk visibility, hydrogen sulfide, free carbon dioxide, CO_3 and HCO_3 alkalinity, total hardness, dissolved solids, specific conductance, and pH.

To test the significance of the difference between sample data group means obtained at stations in and out of the oxygenation site, the Students *t* statistic was employed. Only the sample data group means for dissolved oxygen, water BOD, and sediment BOD were tested. All means were tested at the 0.05 probability level.

On 14 March, 1978 at the end of oxygenation 3, a series of samples was taken on stations 1 through 4, and 5B for analysis by the Water Quality Laboratory, South Dakota State University, Brookings. Sulfate (SO_4) was measured by the turbidimetric method; nitrate (N) by the brucine method; nitrogen (NH_3) by the nesslerization method; nitrogen (organic) by the kehldahl method; phosphate (ortho) by the stannous chloride method; and phosphate (total) by the persulfate digestion and stannous chloride methods.

RESULTS AND DISCUSSION

Physical Conditions

Measurements taken on Round Lake 1 December, 1977, indicated a 0.9 m mean depth and an approximate 186,668 m^3 volume. Ice cover formed on the lake from 1 December, 1977 (20 cm, 17.8% of lake volume), to after 21 March, 1978 (92 cm, 72% of lake volume) (Table 1). From 20 December, 1977, until ice breakup in late March, drifted snow covered Round Lake up to a 60 cm depth. Ice thickness exceeded depth of secchi disk visibility after 20 December, 1977, and until ice breakup, minimal light penetrated the ice and snow cover. Between 19 December, 1977 and 16 February, 1978, 60 consecutive days below freezing occured (a South Dakota record).

Mean temperatures in Round Lake just after freeze-over varied from 1.5 C below the ice to 4.0 C above the sediment (Fig. 6). As winter progressed and ice cover increased, water temperatures gradually decreased. However on 2 March, 1978, measurements indicated that water temperatures had increased slightly, particularly in the area around station 3. Since no thaw had occured prior to this date, the temperature increase could be attributed to sampling error.

Chemical Analysis

In general, the water of Round Lake would be classified

Table 1. Ice and snow conditions and secchi disk visibility on Round Lake during the winter of 1977-1978

Date	Mean Ice Thickness(cm)	Ice Clarity	%Snow Cover	Snow Depth and Condition	Mean Secchi Disk Visibility(cm)
12/1/77	20	Opaque	60-70%	Drifted up to 30cm, dry and packed.	70
12/7/77	20	Opaque	98%	Drifted up to 30cm, dry and packed.	...
12/14/77	30	Opaque	90%	Drifted up to 15-20cm, dry and packed.	...
12/15/77	...	Opaque	40-50%	Drifted up to 20-30cm, wet and packed.	...
12/20/77	36	Opaque	100%	Drifted up to 30cm, dry and packed.	40
1/12/78	59	Opaque	100%	Drifted up to 45cm, dry and packed.	40
1/14/78	...	Opaque	100%	Drifted up to 45-60cm, dry and packed. 2-3cm dusting of dry, loose snow.	...
1/19/78	61	Opaque	100%	Drifted up to 60cm, dry and packed.	...
1/30/78	75	Opaque	100%	Drifted up to 30-60cm, dry and packed.	...
2/4/78	...	Opaque	100%	Drifted up to 30-45 cm, blowing snow.	...
2/12/78	85	Opaque	100%	Drifted up to 30-45 cm, dry and packed. 5-7cm of dry, loose snow on top.	...
3/2/78	92	Clear to opaque	100%	Drifted up to 30-60cm, 7-10cm new snow.	40
3/9/78	...	Shifting, clear to opaque	100%	Drifted up to 30-45 cm, wet and corny.	...
3/12/78	...	Crust breaking, soft and opaque	100%	Drifted up to 15-30cm, wet and slushy.	50

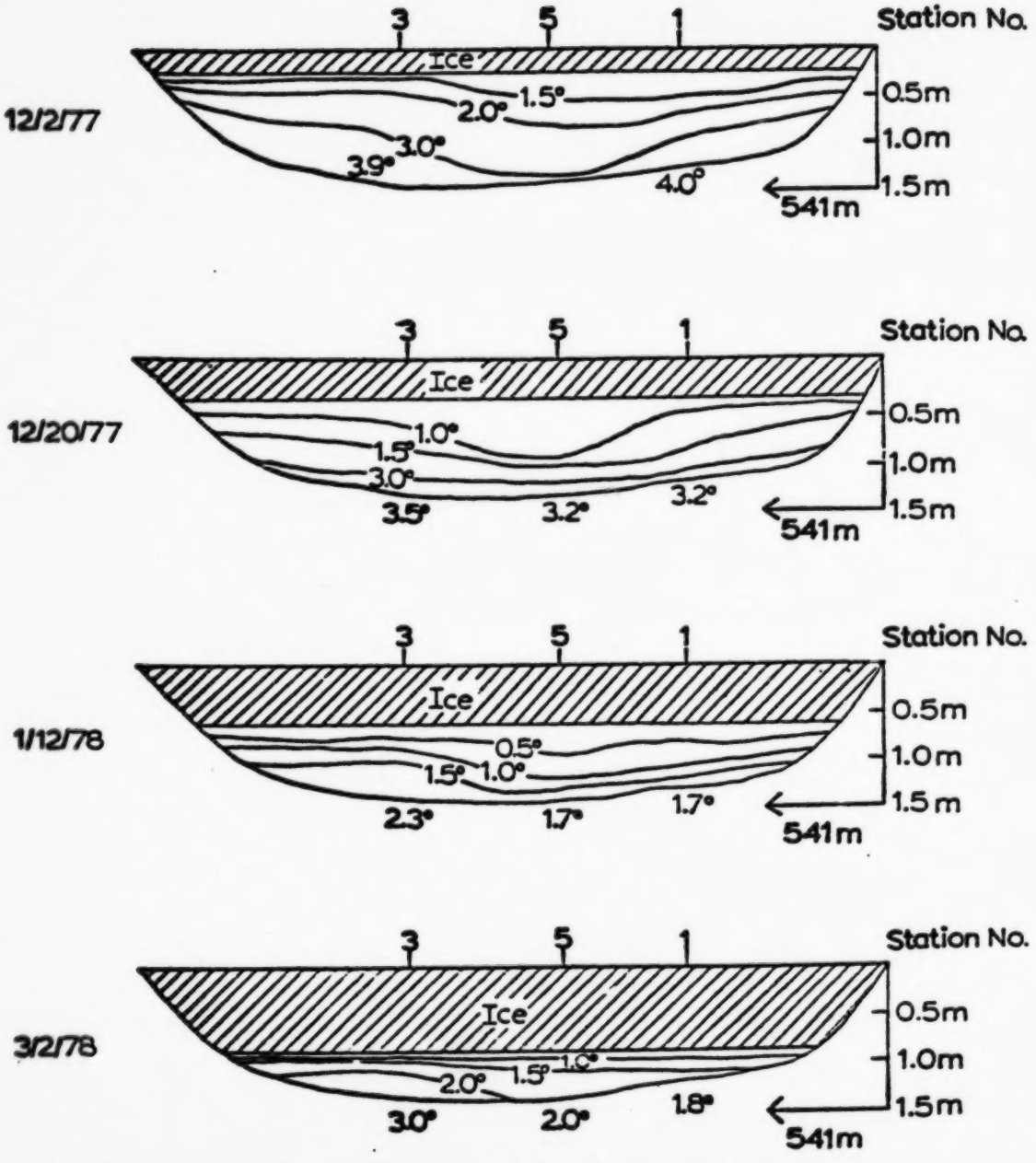


Fig. 6. Profile of Round Lake on a NW to SE axis showing water temperature (C) and ice cover on selected dates, winter of 1977-1978.

as very hard. Dissolved solids, specific conductance, and total hardness all exhibited gradual increases in concentration attributable to the exclusion of ions from ice (Table 2) observed by Gloss (1969). The volume of unfrozen water decreased 81% between 1 December, 1977 and 2 March, 1978. This would explain the maximum percentage increases (based on the initial 2 December sample), in dissolved solids (109%), specific conductance (71%), and total hardness (94%) shown in Fig. 7.

Carbonate alkalinity disappearance after 2 December, 1977 corresponds to the equivalence point (pH 8.3) for the conversion of carbonate ion to bicarbonate ion. The pH decreased from 8.64 to 7.28 as winter progressed (Fig. 8).

The part of the total hardness that is chemically equivalent to the bicarbonate plus carbonate alkalinities present in a water is considered to be carbonate hardness (Sawyer and McCarty 1967). Therefore the increase in carbonate hardness was equal to the bicarbonate alkalinity increase throughout the winter. Carbonate hardness increased from 23% to 33% of the total hardness between 2 December, 1977 and 15 March, 1978. Concurrently the noncarbonate remainder of the total hardness decreased from 77% to 67%. The sulfate ion comprised the majority of this.

In the absence of dissolved oxygen and nitrates,

Table 2. Mean chemical analysis of Round Lake during the winter of 1977-1978 including the corresponding 95% confidence interval

	12/2/77		12/20/77		1/12/78		1/19/78		2/12/78		3/2/78		3/15/78	
	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.
Dissolved Oxygen (mg/l)	12.0	0.8	10.4	2.4	2.6	0.9	0.5	0.4	0	0	0	0	0	0
Free Carbon Dioxide (mg/l)	0.95	0.5	2.6	0.5	8.4	1.6	11.7	3.2	33	4	56	2	59	3
CO_3 Alkalinity (mg/l as $CaCO_3$)	6.1	2.1	0	0	0	0	0	0	0	0	0	0	0	0
HCO_3 Alkalinity (mg/l as $CaCO_3$)	159	1	190	2	270	5	295	3	400	16	446	16	443	15
Total Hardness (mg/l as $CaCO_3$)	704	5	771	21	989	24	1021	10	1234	17	1365	13	1330	52
Dissolved Solids (mg/l)	1135	5	1347	22	1703	22	1737	13	2235	151	2369	75	2342	166
Specific Conductance (umhos/cm2)	1460	30	1633	43	1950	57	2067	65	2383	17	2500	60	2470	114
f=$\frac{\text{Dissolved Solids}}{\text{Specific Cond.}}$	0.78	0.01	0.82	0.01	0.87	0.01	0.84	0.02	0.94	0.06	0.96	0.02	0.95	0.03
pH (units)	8.64	0.02	8.25	0.1	7.92	0.09	7.79	0.11	7.49	0.02	7.32	0	7.28	0.02
Hydrogen Sulfide (mg/l)	0	0	0	0	0	0	0.2	0.2	6.0	3.2	2.0	0.8	1.9	1.1

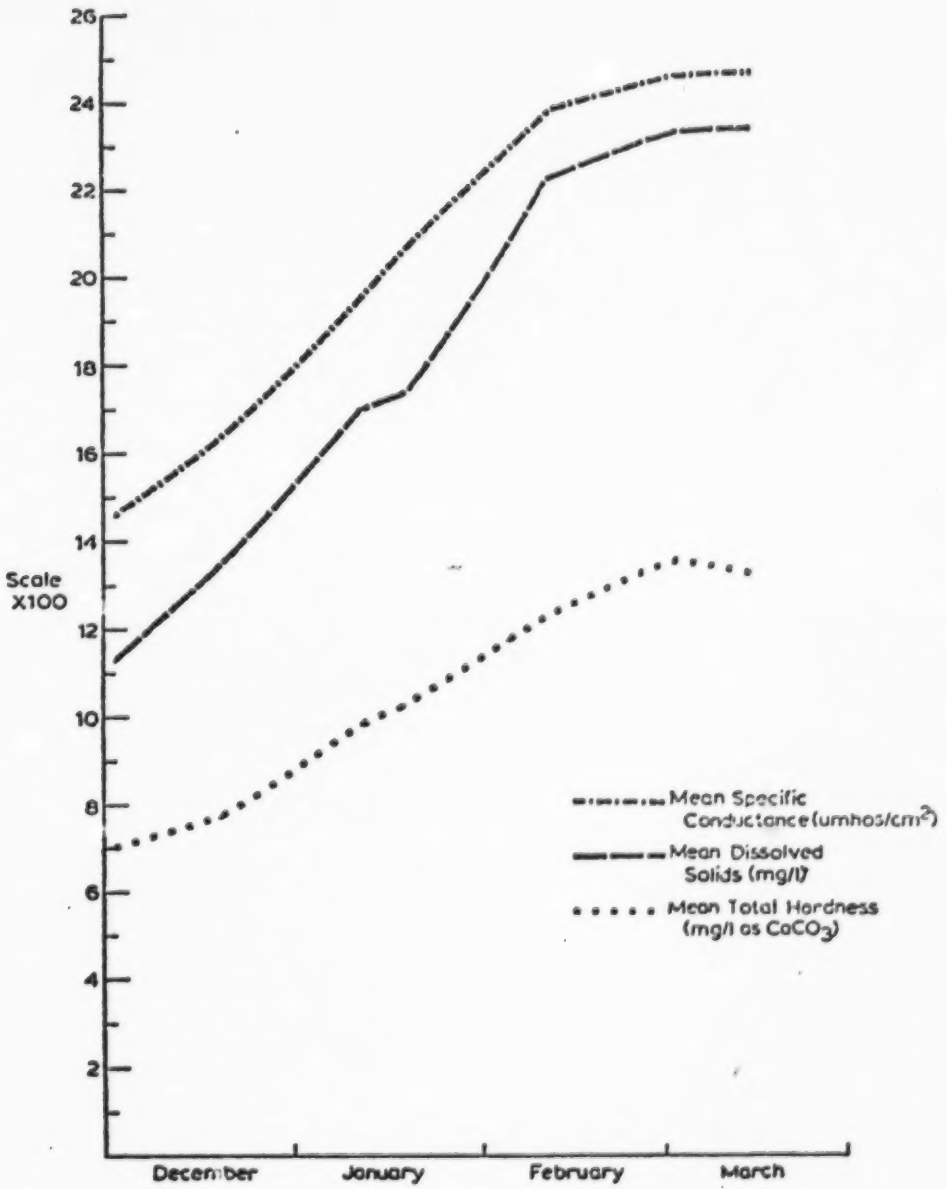


Fig. 7. Comparison of mean specific conductance, dissolved solids, and total hardness concentrations in Round Lake during the winter of 1977-1978.

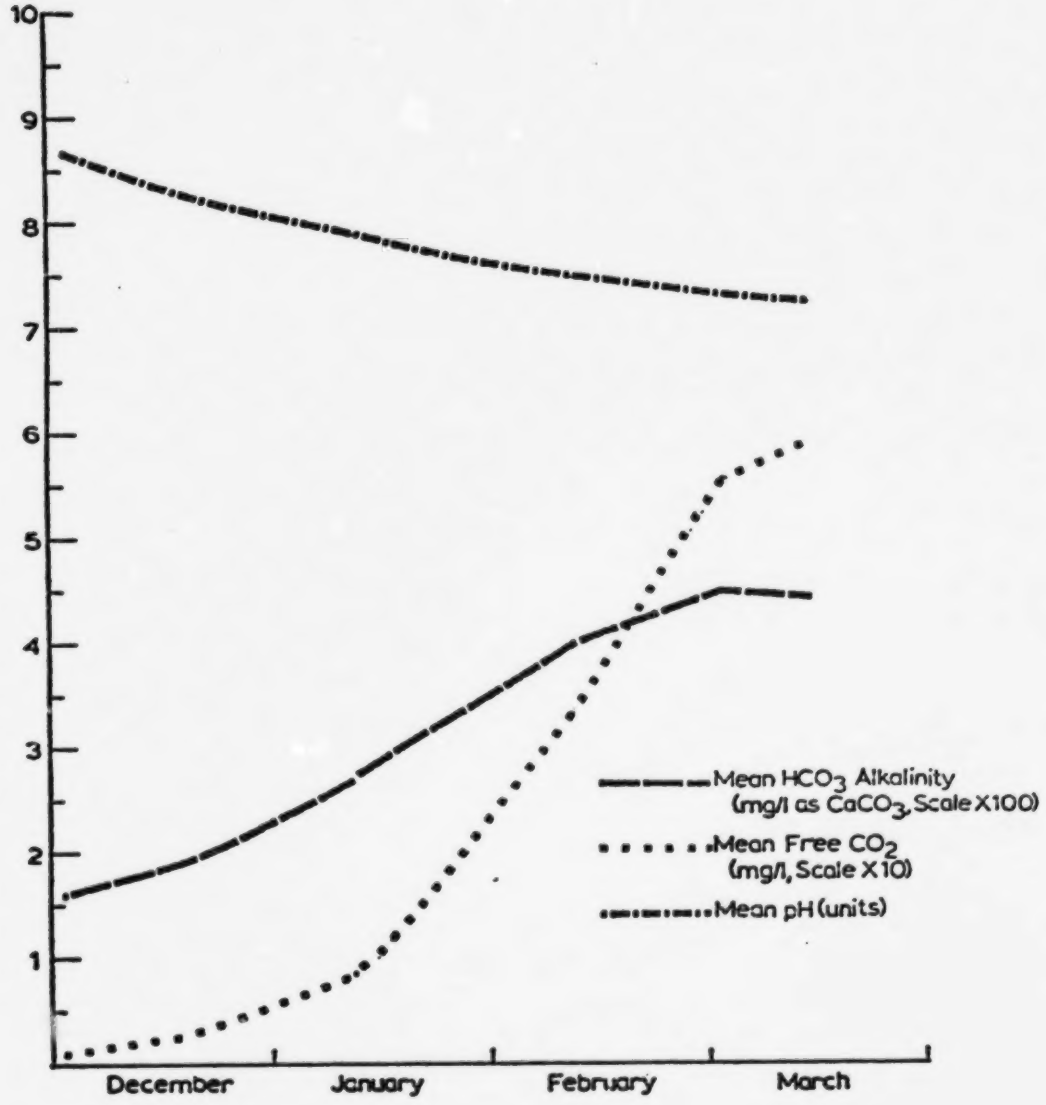


Fig. 8. Comparison of mean HCO_3 alkalinity, free CO_2, and pH in Round Lake during the winter of 1977-1978.

sulfates serve as an oxygen source for biochemical oxidations produced by anaerobic bacteria. Under anaerobic conditions the sulfate ion is reduced to sulfide. At pH levels below 8.0, the equilibrium shifts toward the formation of unionized hydrogen sulfide and is about 80% complete at pH 7 (Sawyer and McCarty 1967). Further, other anaerobic sulfur oxidizing bacteria oxidize hydrogen sulfide and deposit sulfur inside the cell.

Another point of interest was the gradual increase in the factor obtained form the ratio of dissolved solids to specific conductance (Table 2). This factor which once determined is usually constant for a given water body, increased from 0.78 to 0.96 through the winter.

Dissolved oxygen concentrations in Round Lake declined from a 12.0 mg/L mean after ice formation 2 December, 1977 to nearly anoxic conditions (0.5 mg/L mean) by 19 January, 1978. After 19 January, the lake was anoxic until ice breakup. In accord with dissolved oxygen decline and disappearance, hydrogen sulfide gas formation was first detected 19 January, reached a mean maximum (6.0 mg/L) 12 February, then declined to 1.9 mg/L before ice breakup (Fig. 9).

A severe winterkill occured in Round Lake during the 1977-1978 winter. Highly reduced anoxic conditions predominated in the lake from 12 January to late March, and

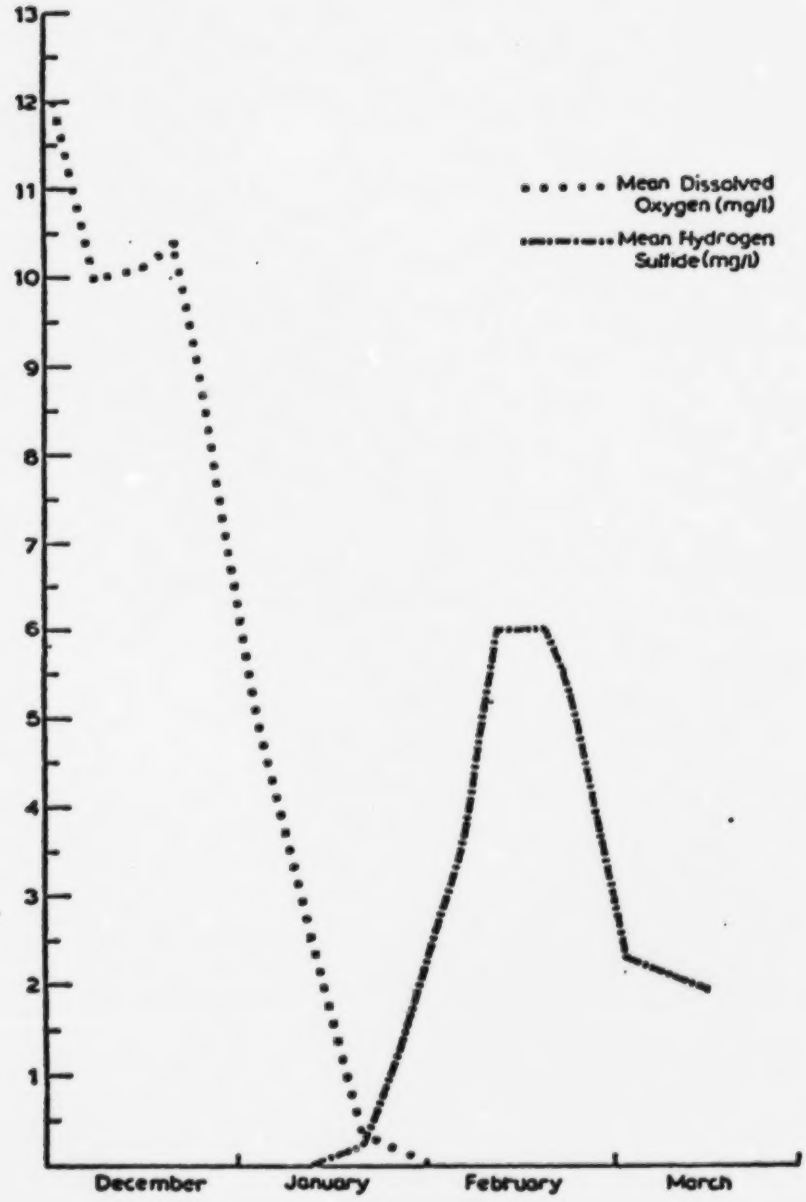


Fig. 9. Comparison of mean dissolved oxygen and hydrogen sulfide levels in Round Lake during the winter of 1977-1978.

concentrations of dissolved gasses toxic to aquatic organisms (carbon dioxide, hydrogen sulfide, and ammonia) reached high levels. Mortality to aerobic aquatic organisms was assumed complete. Even so, sampling on 9 March, 1978 revealed the presence of a live chironomid larva.

Biological Interactions

The results of the diel oxygen method (community metabolism) are shown in Fig. 10. The results by date are presented on a lake mean basis in terms of community respiration (CR), gross photosynthesis (GP), and a ratio of photosynthesis to respiration (P/R). CR varied during the study period from an initial high (1.4 mg O_2/L/24 hrs.) 1-2 December, to a low (0.1 mg O_2/L/24 hrs.) 11-12 January 1978. Only 1-2 and 20-21 December, did the P/R ratio exceed 1.0 indicating net increase in dissolved oxygen during the 24 hour period. On other sampling dates the P/R ratio was below 1.0 and dissolved oxygen decline occured until after 22 January, 1978 no oxygen was detected.

Oxygenation experiment 1, 14 January, 1978 increased the indicated rates of CR and GP in the immediate oxygenation site (Fig. 10). However the P/R ratio was still below 1.0 with a resultant net decline over the 24 hour period in dissolved oxygen. Because the 4 hour oxygenation period preceeded the community metabolism determination on this date, the values were not indicative of the levels which

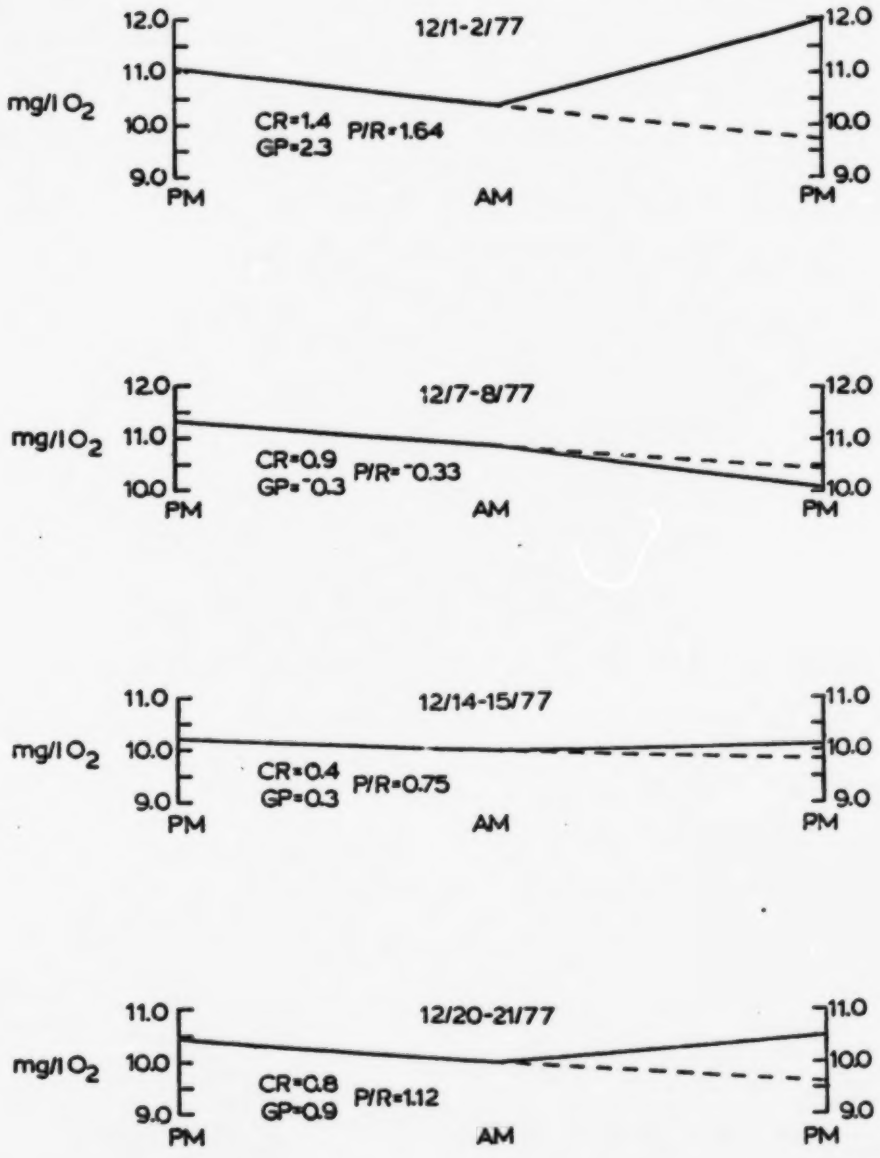


Fig. 10. Mean lake community metabolism by date in Round Lake, winter, 1977-1978.

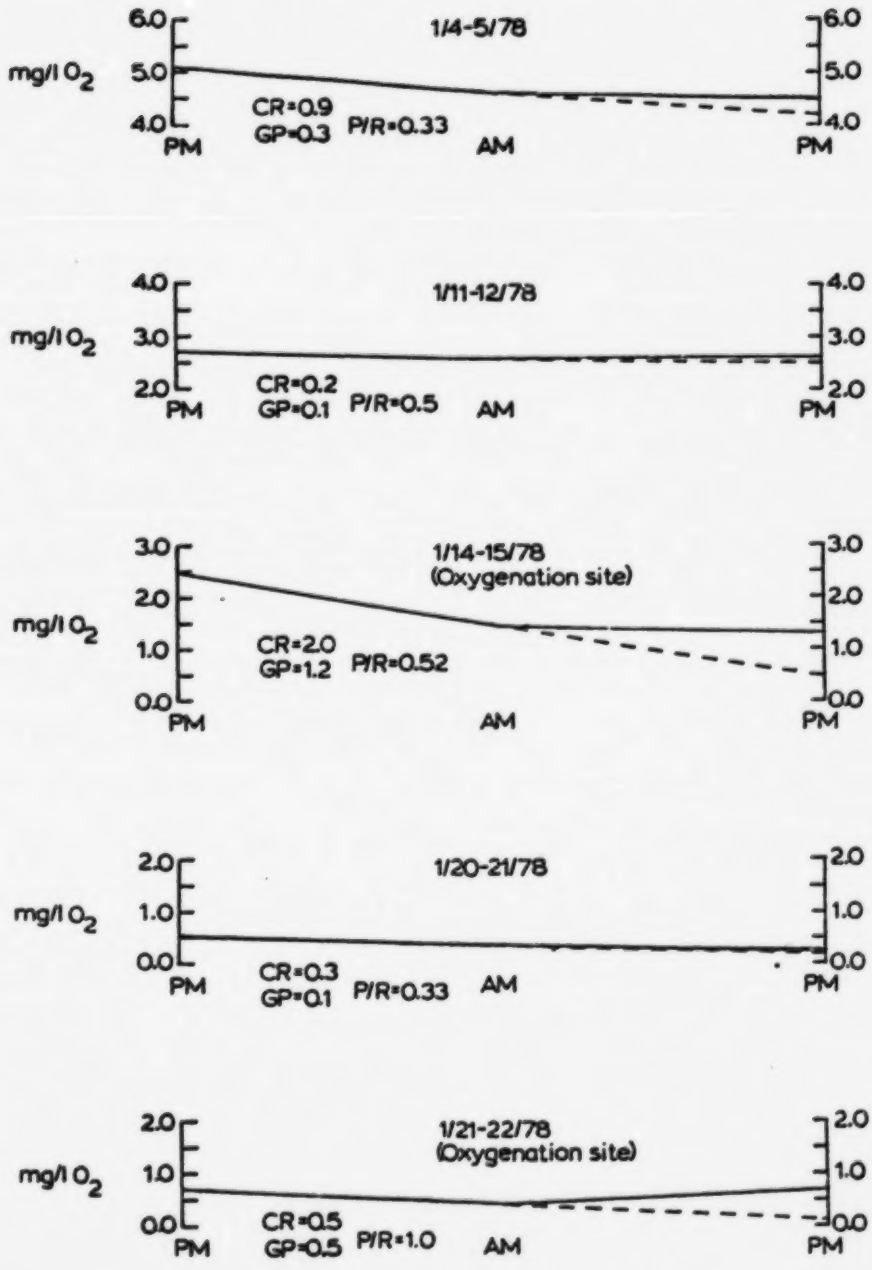


Fig. 10. (continued)

would have been obtained had the oxygenation continued throughout. The community metabolism determination was however a measure of how rapidly oxygen in reaerated water would decline. The P/R ratio after oxygenation was practically unchanged from the mean lake ratio obtained earlier, 11-12 January and would indicate that oxygenation had little effect.

Oxygenation experiment 2, 21-23 January, 1978 slightly increased indicated CR and GP in the immediate oxygenation site (Fig. 10). The 1.0 P/R ratio indicated that GP relative to CR was stable. In experiment 2 oxygenation continued for 48 hours throughout the community metabolism sampling period. No net gain in dissolved oxygen occured after 24 hours. Compared to oxygenation experiment 1, CR and GP rates were reduced. By 21 January, 1978 oxygen demand in the lake water may have been sufficiently high that it was not possible to reaerate enough to effect a meaningful determination of CR. Edberg and Hofsten (1973) found reduction in oxygen consumption with decreasing oxygen concentration. Studies by Hargrave (1969) demonstrated decreased oxygen consumption when dissolved oxygen concentrations fell below 8.6 mg/L. Consequently, during this period measurement of CR by the community metabolism method could have been significantly affected by the low dissolved oxygen values.

Some differences in CR rates between stations (Fig. 11) were noted on each date, but no pattern developed from which inferences could be drawn. The amount of variation could be accounted for by error introduced in the sampling technique. It is also possible that CR at different sample stations was subject to variation. However, the difference between stations shown in Fig. 11 on 20-21 December, 1977, is suspect and probably attributable to sampling error. In general, CR values declined during December, increased slightly during the first week of January, then declined again during the balance of January.

The effect of oxygenation experiment 1 on CR at each sampling station in the oxygenation area is shown 14-15 January (Fig. 11). In addition, little effect by station (within the oxygenation area) on 21-22 January is shown for oxygenation experiment 2.

When dissolved oxygen in Round Lake was depleted, it was necessary to abandon the community metabolism method and obtain water respiratory oxygen demand measurements by the BOD method described in American Public Health Association (1971). The BOD determinations are shown in Figure 12 from 12 February through 22 March, 1978. Initially both light and dark bottles were used to determine if any oxygen production was evident in the water. The results indicated no difference between light and dark bottles. Consequently

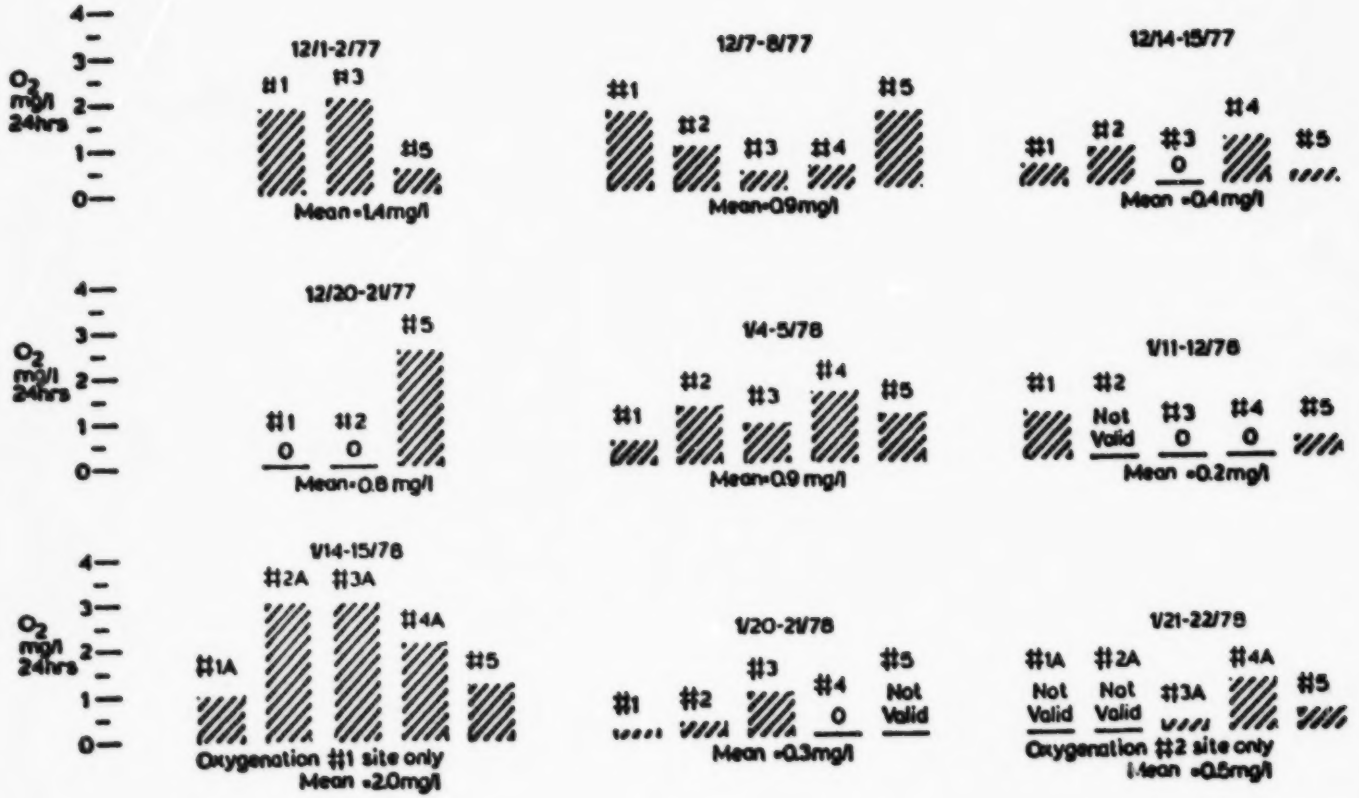


Fig. 11. Total community respiration at each station on Round Lake by the community metabolism method.

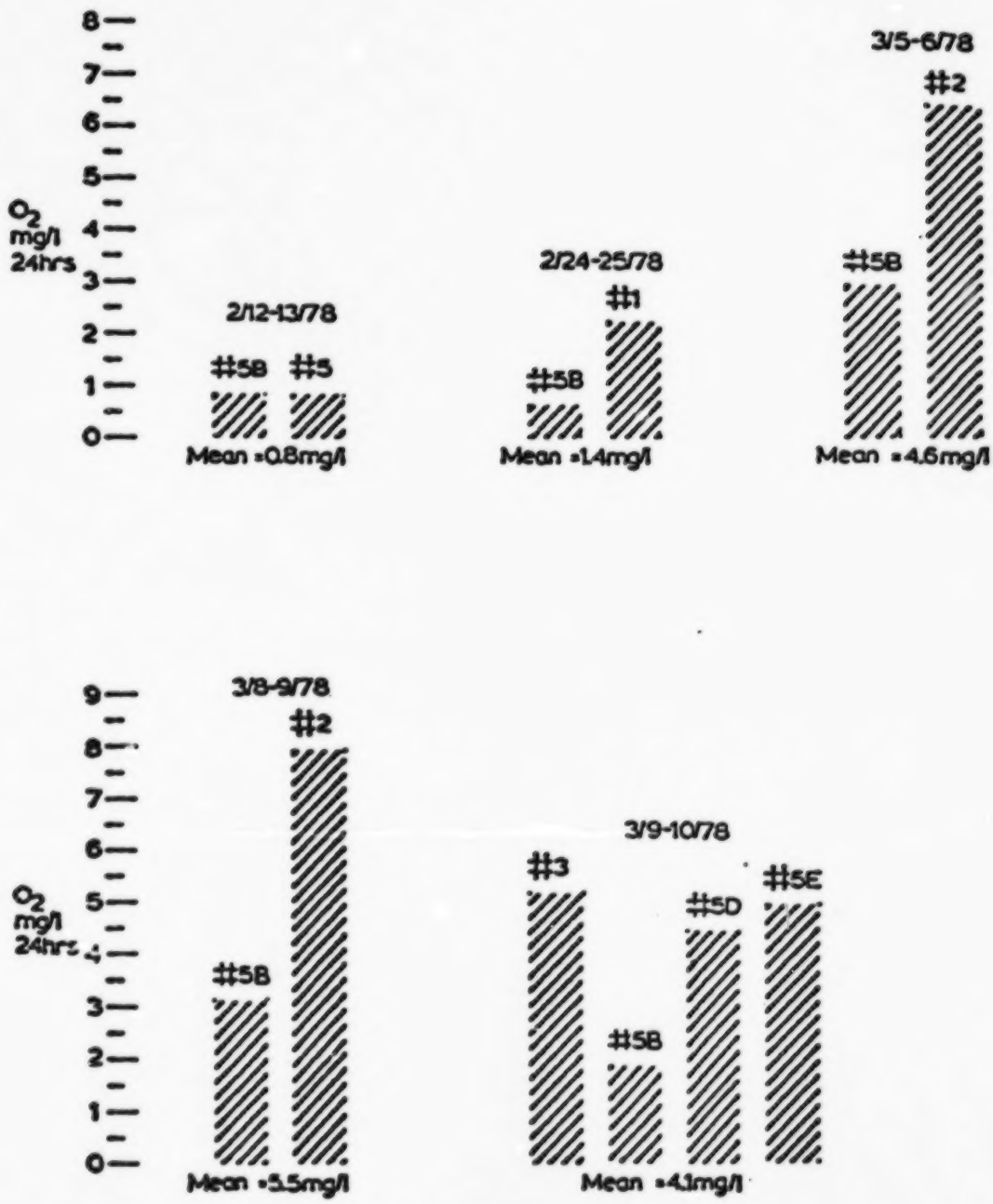


Fig. 12. 24 hour lake water BOD by date at selected stations on Round Lake, winter, 1977-1978.

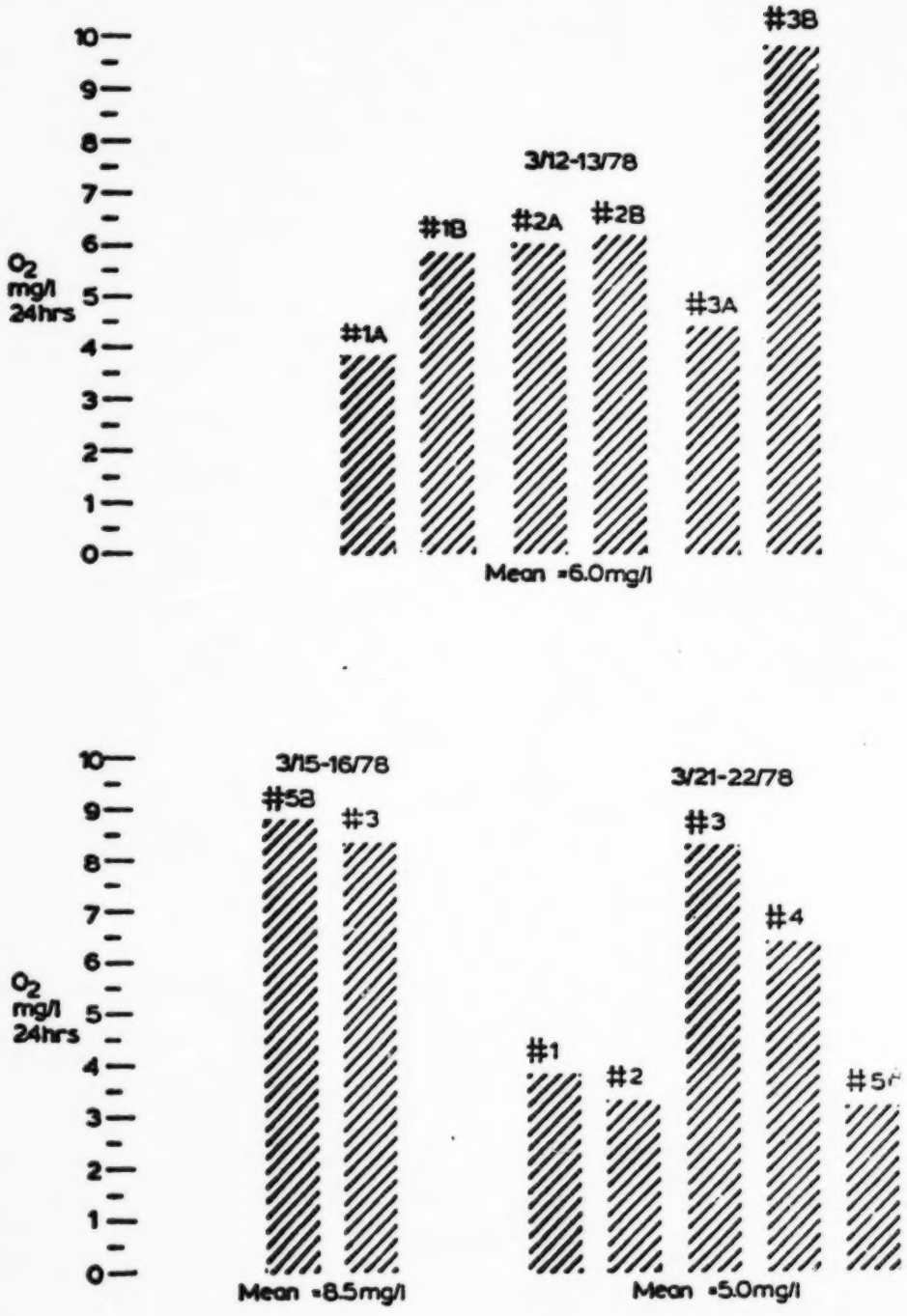


Fig. 12. (continued)

determinations were made only of BOD. Johnson (1960) in his study on Christie Pond in Brookings County, also found no difference between light and dark bottles suspended under the ice during winterkill.

Water samples 12-13 and 24-25 February, 1978 were not diluted. The BOD determination 5-6 March, 1978 was made with water diluted 45% and samples after that date were diluted 80%. This dilution was necessitated by increasing lake water oxygen demand. In the final BOD calculation, a correction is made for the dilution so all values in Figure 12 are expressed as undiluted lake water BOD.

Bottle incubation under the ice instead of the standard 5 day BOD at 25 C was done to obtain an in site measurement of BOD. The 24 hour incubation time was chosen because longer incubation often resulted in complete dissolved oxygen depletion in the sample bottles. In addition, removal of the bottles and suspending ropes from under the ice with longer incubation was difficult due to freezing of the holes.

The values measured by the undiluted and diluted water BOD method, are within the range measured by the community metabolism method. This would lead to the assumption that measurements of community respiration obtained by

both methods are comparable. The pattern shown throughout the entire sampling period, revealed that CR values generally declined to the end of January and BOD values increased until the middle of March. Johnson (1960), measuring 5 day BOD, obtained similar results on Christie Pond. A severe winterkill occurred on Christie Pond during the study. If the 5 day BOD values he obtained are averaged into 24 hour values, they are within the range of 24 hour water BOD values recorded for Round Lake.

The high BOD values in February and March can be explained by the reduction processes resulting from bacterial action. These bacteria remove oxygen from the sulfates and to a lesser extent the phosphates, nitrates, and other organic compounds. All of these can then be oxidized in the presence of dissolved oxygen. BOD tests with anaerobic water and oxygenated dilution water result in oxygen being utilized in initial organic content oxidation, in reforming the sulfates, phosphates, and nitrates, and in oxidation of residues resulting from anaerobic bacterial action. Oxygen demand of anaerobic water exhibits an increase in BOD over that expected with aerobic conditions as a result (Johnson 1960).

Samples taken outside the oxygenation site generally showed gradual increase in BOD until ice breakup. A complete set of samples taken outside the oxygenation site March 21 (Fig. 12), indicated that dilution due to melt water had begun to decrease the BOD in the lake water.

Due to their reductive characteristics and high content of soluble nutrients, the sediments of prairie pothole lakes are the major source of reducing matter causing depletion of dissolved oxygen during the winter (Barica 1974). Edberg and Hofsten (1973) stated that the sediment is of maximal significance for the oxygen balance when the water depth is shallow and the overlying water contains only a minimal amount of oxidizable matter. Hayes and MacAulay (1959) and Hargrave (1972) showed that sediment oxygen consumption could account for all the observed hypolimnetic oxygen deficit in their lakes. A determination of sediment BOD was therefore important to the determination of the total lake BOD.

The alum flocculation modification of the Winkler method was chosen to determine the dissolved oxygen in the sediment BOD bottles because it removes iodine consumption interference in samples high in suspended solids. Ruchhoft and Moore (1940) found that with the alum flocculation procedure there was little interference in the

initial dissolved oxygen determination. In their studies the results obtained following the alum flocculation procedure were more reliable and produced closer approximations to the total oxygen demand of the mud under examination.

The depth to which the lake sediment effects the dissolved oxygen content in the overlying water is a matter of conjecture. Edberg and Hofsten (1973) found that a layer a few mm deep on top of the sediments was aerobic, but that the reduced products of decomposition could be transported from the anaerobic zone to the aerobic sediment and further into the water. Hayes (1955) showed that almost all activity in the mud is concentrated in a layer at the surface estimated as less than 0.5 mm thick. Neame (1975) in his study on Castle Lake, California, determined that oxidation-reduction profiles usually showed a distinct minimum at 2-3 cm below the interface. Edwards and Rolley (1965) found that oxygen consumption was independent of sediment depth at depths greater than about 2 cm. The results of 24 hour sediment BOD analyses on Round Lake during February and March (Fig. 13) indicated that the sediment BOD during the sample period was 10 to 15 times that of the water in the lake.

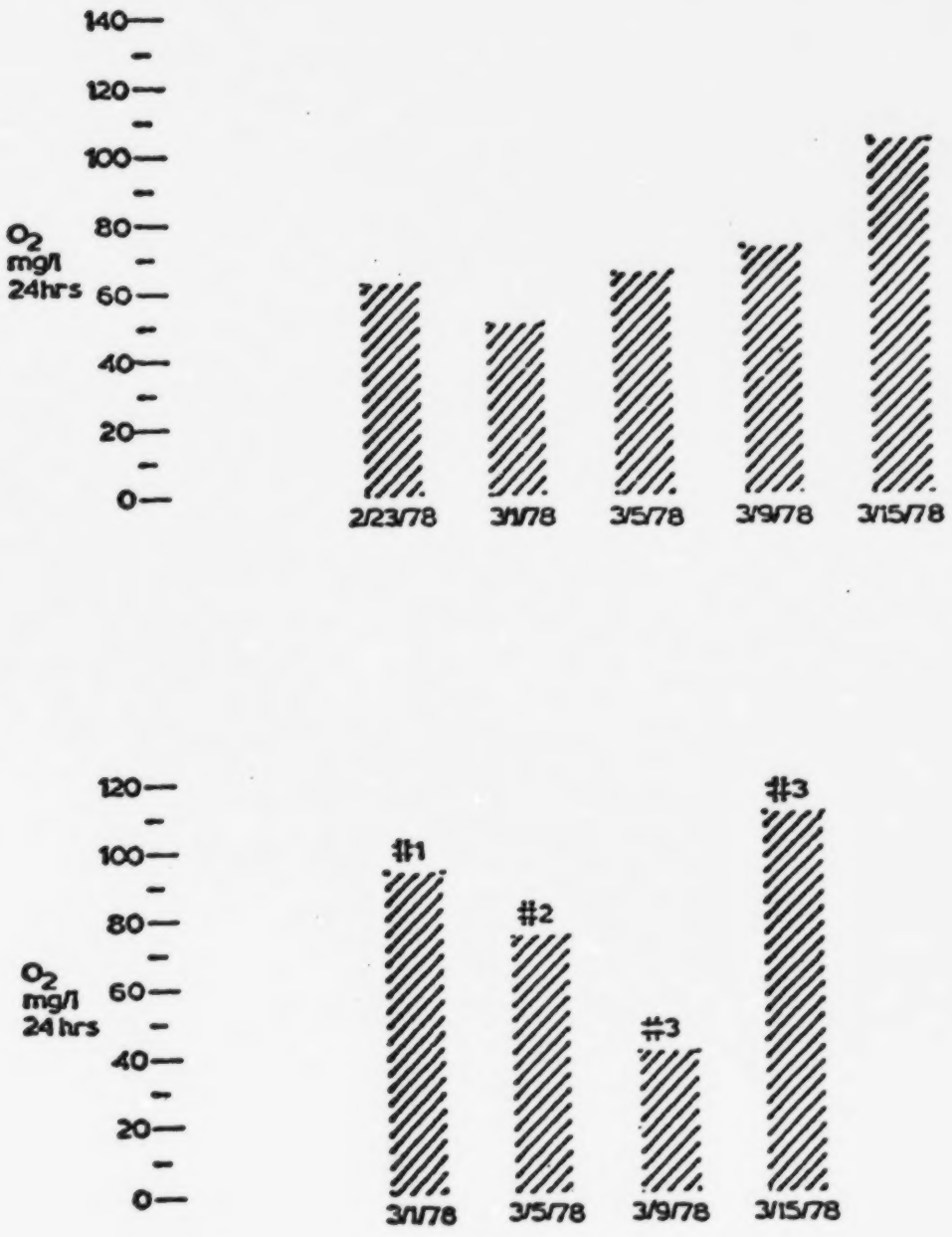


Fig. 13. 24 hour sediment BOD in Round Lake, winter, 1977-1978. Above: Station 5B by date. Below: Stations 1,2, and 3 by date

Phytoplankton cell counts (Fig. 14) indicated that during ice cover no phytoplankton species was particularly predominant or exhibited any significant increase. Four genera, Ankistrodesmus, Aphanocapsa, Chlamydomonas, and Euglena, were most abundant. Identifiable phytoplankton comprised from 6.3% to 13.0% by number of total cells counted throughout the winter. Mean identifiable phytoplankton numbers increased from 3167/ml 2 December to 6175/ml 20 December, 1977, then steadily declined the duration of the winter to a 1668/ml level 15 March, 1978. It is possible that some of the small unicellular flagellates that predominate under ice cover may have been lost or destroyed due to centrifuging and preservation.

In conjunction with phytoplankton cell counts and utilizing identical sampling and preservation techniques, an evaluation was made of bacteria and aquatic fungi numbers. The results indicated that bacteria and fungi comprised from 87.0% to 93.7% by number of the total cells (phytoplankton, bacteria, and fungi) in the lake water under ice cover (Fig. 14).

Counting and identifying bacteria and fungi is difficult, and many cells probably were overlooked. In addition, identification to genus is tentative. Knowledge of the physiology, biochemistry, and reproduction of bacteria and

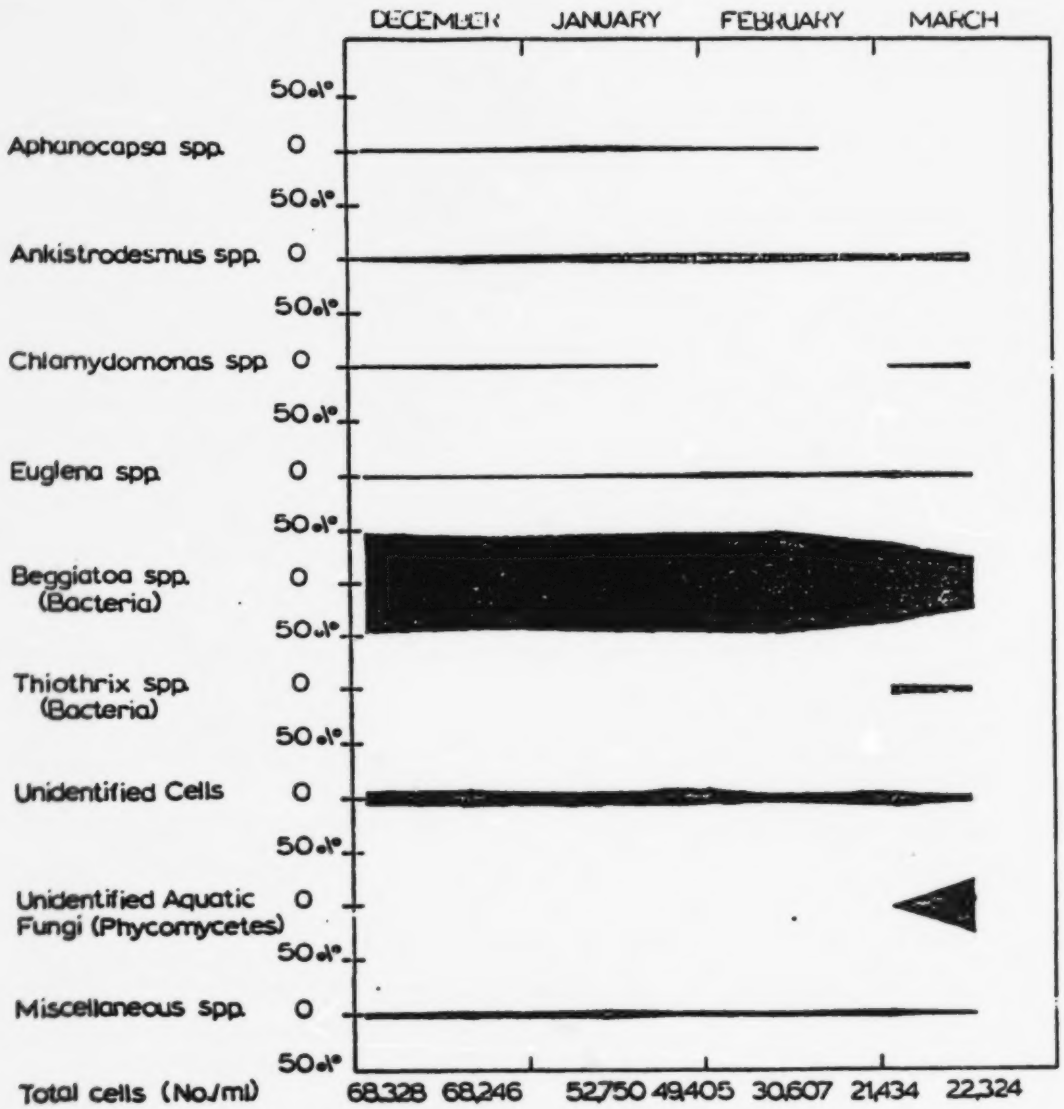


Fig. 14. Plankton percent composition by number of cells, colonies, or filaments, and total cells (no./ml). Miscellaneous genera comprising less than 1% of the population were: Agmenellum, Scenedesmus, Kirchneriella, Actinastrum, Glenodinium, Cryptomonas, Stichosiphon, Micractinium, Melosira, Phacus, Tetraedron, Schroederia, Navicula, and Golenkinia.

fungi is required for positive identification. All identification in this study was done on the basis of morphology and limited knowledge of the physiology of the organism. Beggiatoa, a long filamentous bacterium, and Thiothrix are common bacteria that oxidize hydrogen sulfide with deposition of sulfur intracellularly and occur in areas where hydrogen sulfide is being formed (Wetzel 1975). Many aquatic fungi (Phycomycetes) species are parasitic on algae in the plankton and benthos as well as saprobic on dead organic matter (Cooke 1963), which may explain their presence.

Chlorophyll and plant pigment analysis was conducted as another measure of phytoplankton abundance during ice cover. The decline in mean chlorophyll a concentrations (Table 3) correspond closely with the decline in identifiable phytoplankton numbers. Phytoplankton numbers declined 73% from 29 December to 15 March, 1978, while mean chlorophyll a concentration during the same time period declined 70%. The increase in chlorophyll b concentration may have been related to the slight increase in Euglena spp. numbers. Euglenophyceae have been shown to contain quantities of chlorophyll b, unlike most other phytoplankters (Wetzel 1975).

Table 3. Mean chlorophyll and plant carotenoid levels in Round Lake during the 1977-1978 winter

Date	Chlorophyll a (Mean mg/l)	Chlorophyll b (Mean mg/l)	Chlorophyll c (Mean mg/l)	Plant Carotenoids (Mean mg/l)
12/20/77	46.6	0	5.7	6.0
1/12/78	20.8	0	0	3.2
1/19/78	29.2	0	7.2	6.0
2/12/78	26.0	0.8	5.6	5.4
3/2/78	22.5	0.8	6.0	5.5
3/15/78	14.1	1.9	5.5	3.2

Chlorophyll concentration is often used as an estimator of phytoplankton biomass. However, much of this chlolophyll may be non-active. This could be expected expecially during winterkill conditions. Degraded forms of inactive chlorophyll (phaeopigments) interfere with the spectrophotometric determination of chlorophylls because they absorb light in the same region of the spectrum. Strickland and Parsons (1968) presented a procedure whereby the concentration of phaeopigments could be measured and a correction made for the chlorophyll a determination. This procedure was included as part of the standard pigment analysis on Round Lake, but meter drift after acidification rendered the spectrophotometer absorption readings inaccurate. Consequently, chlorophyll readings should be interpreted as a measure of both the active and inactive fractions.

Oxygenation Experiment 1

The mean dissolved oxygen level in Round Lake 12 January, 1978 was 2.6 mg/L. Two days later, 14 January, prior to oxygenation, the mean dissolved level (from sample sites 1A-4A, and 5) had declined in the oxygenation site to 1.9 mg/L. After 4 hours of oxygenation, a total of 1,200 L of molecular oxygen gas was released at 5 L/min., and the mean dissolved oxygen level (from sample sites

1A-4A, and 5) had increased to 2.4 mg/L. The dissolved oxygen increase was significant at sample sites 2A, 3A, and 4A as determined by the Student's *t* test.

To determine how the molecular oxygen effects had dispersed from the oxygenation site, dissolved oxygen measurements were taken at the B and C holes; located 3 and 6 m respectively from each air stone. The mean dissolved oxygen level at both the B and C sampling sites was 1.9 mg/L. There was a significant decrease at all B and C sampling sites compared to those in the oxygenation area (1A-4A, and 5). Therefore, no dissolved oxygen dispersal was indicated outside the immediate area of the air stones. The mean dissolved oxygen level (from sample sites 1A-4A, and 5) had declined to 1.3 mg/L 24 hours after oxygenation. The decline was significant at all sample sites. From these results and the community metabolism findings, it was concluded that oxygenation experiment 1 had little immediate effect and no permanent effect towards winterkill prevention.

Oxygenation Experiment 2

The mean dissolved oxygen level in the oxygenation site prior to oxygenation experiment 2, 21-23 January, 1978 had declined to 0.8 mg/L. After 24 hours of oxygenation at 10 L/min., a total of 28,800 L of molecular oxygen gas was released and the mean dissolved oxygen level (from

sample sites 1A-4A, and 5) had increased to only 0.9 mg/L. The increase was not significant at any of the sampling sites (1A-4A, and 5). After oxygenation for 48 hours at the same rate no dissolved oxygen could be detected at any of the sampling sites. There was a significant decrease at all sample sites.

Test netting conducted during oxygenation collected no fish. From these results and the community metabolism findings, it was concluded that continuous oxygenation utilizing the stone pattern and strategy employed in experiments 1 and 2 would not be effective in preventing winterkill. It was evident that BOD of the lake was exceeding the capacity of the molecular oxygenation apparatus to reaerate the water.

Oxygenation Experiment 3

The interval between oxygenation experiment 2 and 3 showed dissolved oxygen reduced to anoxic conditions throughout Round Lake. More stones (6) were placed closer together than in experiments 1 and 2 to present a more concentrated oxygenation effect (Fig. 5). Between 1 February and 14 March, 1978, 681,400 L of molecular oxygen gas was released under the ice. After oxygenation for 72 hours, the mean dissolved oxygen level (from sample sites 5A, 5B, and 5C) had increased to 1.1 mg/L. However, 48 hours later the mean dissolved oxygen level from the same

sample sites had decreased to 0.1 mg/L and no dissolved oxygen was detected in the oxygenation site for the remainder of the experiment. The decrease was significant at sample sites 5B and 5C.

Observations during oxygenation indicated first that oxygen bubbles after ascending to the ice, were immediately migrating to sample holes drilled in the ice and escaping to the atmosphere. An effort was made to allow the holes to freeze over, but the oxygen bubbles invariably kept most of the holes partially open. A green hydrogen sulfide smelling foam was consistently emitted from the sample holes. Sampling at newly drilled holes (5E), 9 March did however indicate from the gas pressure released upon breaking through the ice, that some molecular oxygen gas was being trapped under the ice and retained.

Ice loss above the oxygenation site was not observed until 16 February, 15 days after the initiation of oxygenation experiment 3. Open water did not appear above the oxygenation site until 12 March, 40 days after the initiation of oxygenation. Measurements at the end of all oxygenation 14 March, indicated that ice thickness in approximately 300 m^2 around the oxygenation site was affected. The area immediately above the oxygenation site represented about 45 m^2.

The failure of molecular oxygenation to increase and sustain dissolved oxygen in Round Lake led to comparisons between the oxygenation area and unoxygenated areas of the lake. Water BOD tests conducted during oxygenation (Fig. 12) indicated that BOD outside the oxygenation site was usually more than twice the values at the oxygenation site (5B). The comparison 12-13 February, 1978 indicated no significant difference between the BOD at sample site 5B compared to that outside the oxygenation site at sample site 5. A BOD sample series taken at sample sites 5B, 5D, and 5E 9-10 March, 1978, showed that the BOD increased significantly with distance from the oxygenation site. The same significant BOD increase was indicated from the analysis 12-13 March, 1978 comparing sample sites 1A to 1B and 3A to 3B. Oxygenation experiment 3 was concluded 14 March, 1978. A comparison between sample site 5B and sample site 3, 15-16 March, indicated that within 24 hours after oxygenation no significant difference could be detected. No pattern of BOD decline or increase within the oxygenation site (sampling site 5B) was revealed.

Sediment BOD analyses during the same time period (Fig. 13) demonstrated no significant oxygenation effects. The lowest BOD measured, 9 March, 1978, was at sample site 3, outside the oxygenation area.

Water temperature measurements were taken 2 March,

after 30 days of continuous oxygenation, both in (5B) and outside the oxygenation site. Fig. 6 summarizes the temperature stratification and ice cover measurements on the lake. Since 92 cm of ice covered the lake by this date it was not possible to take readings at the 0.5 m level. Mean temperature for the entire lake at 1.0 m was 1.4 C and 5 cm above the bottom 2.4 C. Ice cover in the oxygenation area by 2 March had decreased to 25 cm at sample site 5B. Temperature readings of 1.4 C at 0.5 m, 1.4 C at 1.0 m, and 2.0 C 5 cm above the bottom were obtained at sample site 5B. Compared to the entire lake mean value, these readings indicated mixing and homogenization of the temperature stratification due to aeration.

On the same date, secchi disk visibility readings outside the oxygenation site averaged 0.4 m, while the reading at sample site 5B was 0.3 m, indicating sediment mixing could be the cause of the decreased light penetration because the aeration stones rested on the bottom. This situation was unavoidable, but may have been a source of increased water BOD in the oxygenation site.

Tables 4 and 5 contain the results of chemical analyses comparing stations outside and inside the oxygenation site 14-15 March. Spring water was observed flowing into Round Lake in the vicinity of station 2: thus the analysis at station 2 indicated melt water inflow.

Table 4. Chemical analysis comparing stations on Round Lake, March 15, 1978

	Station				
	1	2	3	4	5B
Free Carbon Dioxide (Mean mg/l)	63	54	58	60	62
HCO_3 Alkalinity (Mean mg/l as $CaCO_3$)	445	412	454	449	454
pH (Mean units)	7.26	7.32	7.29	7.28	7.27
Hydrogen Sulfide (Mean mg/l)	0.4	0.4	3.5	3.5	1.5
Total Hardness (Mean mg/l as $CaCO_3$)	1340	1227	1375	1362	1345

Table 5. Chemical analysis comparing stations on Round Lake, March 14, 1978

	Station				
	1	2	3	4	5B
Sulfate (SO_4) (Mean mg/l)	1213	1013	1163	1175	1213
Nitrate (N) (Mean mg/l)	0.22	0.22	0.22	0.26	0.26
Nitrogen (NH_3) (Mean mg/l)	18.00	17.00	17.00	18.00	18.00
Nitrogen (Organic) (Mean mg/l)	2.07	1.29	2.51	7.20	2.67
Phosphate (Ortho) (Mean mg/l)	0.14	0.15	0.15	0.12	0.09
Phosphate (Total) (Mean mg/l)	0.34	0.40	0.40	0.49	0.34

Cost-Benefit Discussion

Attempts to prevent winterkill on Round Lake utilizing molecular oxygen during the winter of 1977-1978 were unsuccessful. It was shown however that molecular oxygenation did have an effect in reversing the chemical and biological interactions leading to anoxic conditions.

From measurements of the water and sediment oxygen demand throughout the winter and knowledge of the lake and sediment volume, it was possible to make an estimate of the total lake oxygen demand for the 4 month winter period. Extending the closest measurement time-wise to include periods in which measurements were not taken, would bias the total lake oxygen demand estimation, so it must be remembered that this is only an approximation. The approximation was undertaken solely to estimate how much molecular oxygen might have been required to prevent anoxic conditions in Round Lake during the 1977-1978 winterkill. It should be noted that the 1977-1978 winterkill was severe throughout the state and consequently would not be indicative of an average winter. The measurements taken were valuable however, in that they approached the worst extreme that could be expected.

The approximate total lake oxygen demand determined in Round Lake for the period from December through March was 1.50×10^5 kg O_2 or 1.05×10^8 L at O C and 760 mm Hg

pressure. From these figures and assuming 100% molecular oxygen gas dissolution into the lake water, the amount of oxygen pumped into Round Lake would represent approximately 0.7% of the amount that would have been required to satisfy the oxygen demand and raise the dissolved oxygen level to 5 mg/L.

The total lake oxygen demand (1.05×10^8 L) would require 823 Gas Pack 45 oxygen tanks over a 4 month winter period. At a cost (during the period of this study) of approximately $85.00 per tank or 46¢/kg of molecular oxygen, this would represent an indicated total expenditure of $70,000 for oxygen alone. Speece (1969) indicates that for a 3 month per year usage the cost of molecular oxygen would be 2¢ to 6¢/kg depending on the location and quantity used. Apparently, the cost of molecular oxygen is variable dependent upon the total amount used and source of supply.

The assumption of 100% molecular oxygen dissolution efficiency is obviously invalid. Speece (1969) investigated use of molecular oxygen under various conditions and found 100% oxygen absorption in a 2 mm diameter bubble released in 20 C water at 30 m. His studies indicated that a 2 mm diameter bubble released at a 1.5 m depth would have a total oxygen absorption of about 19%. Since the bubbles released from the graphite air stones averaged about 2 mm diameter and the depth in the oxygenation area on Round Lake was 1.4 m,

a total oxygen absorption efficiency of only about 19% may have been realized. This would consequently increase the amount of oxygen required for reaeration and the indicated cost approximately 5 times to $350,000 on Round Lake.

It may be more feasible to create a "refuge" situation within a larger lake, oxygenating only a limited lake area, probably the deepest contour. Speece (1969) found that the deeper a bubble of molecular oxygen is released the greater the total oxygen absorption into the water before it reaches the surface. Thus a 2 mm bubble released in 3 m of water, (such as occurs in East and West Oakwood Lakes) would have a predicted 33% total oxygen absorption before reaching the surface.

Much more research is needed in this area. More efficient molecular oxygenation systems such as the downflow bubble contact system proposed by Speece (1969), and the side stream pumping system proposed by Fast et al. (1975) warrant investigation. However, it must be remembered that oxygenation of any body of water is a "cosmetic" approach, treating only the symptoms of the disease, not solving the problems. Eutrophication and sedimentation of prairie pothole lakes are the primary winterkill causative factors, and the long term solution is to prevent these factors.

LITERATURE CITED

Amberg, H.R., D.W. Wise, and T.R. Aspitarte. 1969. Aeration of streams with air and molecular oxygen. TAPPI 52: 1866-1871.

American Public Health Association. 1971. Standard methods for the examination of water and wastewater. APHA. New York. 874 pp.

Barica, J. 1974. Extreme fluctuations in water quality of eutrophic fish kill lakes: effect of sediment mixing. Water Res. 8(11):881-888.

Cooke, W.B. 1963. A laboratory guide to fungi in polluted waters, sewage, and sewage treatment systems. Public Health Service Publ. No. 999-WP-1. 132 pp.

Edberg, N. and B.V. Hofsten. 1973. Oxygen uptake of bottom sediments studied in situ in the laboratory. Water Res. 7:1285-1294.

Edwards, R.W. and H.L. Rolley. 1965. Oxygen consumption of river muds. J. Ecol. 53(1):1-19.

Fast, A.W., W.J. Overholtz, and R.A. Tubb. 1975. Hypolimnetic oxygenation using liquid oxygen. Water Resour. Res. 11(2):294-299.

Gloss, S.P. 1969. Water quality changes under ice cover in northern prairie lakes. M.S. Thesis, South Dakota State Univ., Brookings. 59 pp.

Hargrave, B.T. 1969. Similarity of oxygen uptake by benthic communities. Limnol. and Oceanogr. 14:801-805.

Hargrave, B.T. 1972. A comparison of sediment oxygen uptake, hypolimnetic oxygen deficit, and primary production in Lake Esrom, Denmark. Verh. Int. Ver. Limnol. 18:134-139.

Hayes, F.R. 1955. The effect of bacteria on the exchange of radiophosphorus at the mud-water interface. Verh. Int. Ver. Limnol. 12:111-116.

Hayes, F.R. and M.A. MacAulay. 1959. Lake water and sediment. V. Oxygen consumed in water over sediment cores. Limnol. and Oceanogr. 4:291-298.

Johnson, J.L. 1960. Some limnological conditions relative to winterkill of fish in ice covered representative farm ponds in eastern South Dakota. M.S. Thesis, South Dakota State Univ., Brookings. 52 pp.

King, D.L. 1970. Reaeration of streams and reservoirs, analysis and bibliography. U.S. Bur. Rec. Tech. Rept. REC-OCE-70-55. 131 pp.

LaBounty, J.F. and D.L. King. 1977. Reaeration. Presentation at a conference entitled "Mechanics of Lake Restoration", April 25-28, 1977. Wisconsin Center, Madison, Wisconsin.

Lackey, J.B. 1938. The manipulation and counting of river plankton and changes in some organisms due to formalin preservation. U.S. Public Health Repts., 53:2080-2093.

Lorenzen, M. and A.W. Fast. 1977. A guide to aeration/ circulation techniques for lake management. Environ. Prot. Agency. Ecol. Res. Series, EPA-600/3-77-004. 126 pp.

McConnel, W.J. 1962. Productivity relations in carboy microcosms. Limnol. and Oceanogr. 7:335-343.

National Academy of Sciences. 1969. Eutrophication: causes, consequences, correctives. National Academy of Sciences, Washington D.C. 661 pp.

Neame, P.A. 1975. Oxygen uptake of sediments in Castle Lake, Calif. Verh. Int. Ver. Limnol. 19:792-799.

Prescott, G.W. 1962. Algae of the western Great Lakes area. Wm. C. Brown Co., Dubuque, Iowa. 977 pp.

Prescott, G.W. 1970. How to know the freshwater algae. Wm. C. Brown Co., Dubuque, Iowa. 348 pp.

Prevot, A.R. 1966. Manual for the classification and determination of the anaerobic bacteria. (Translated by V. Fredette). Lea and Febiger, Phila., Pa. 402 pp.

Ruchhoft, C.C. and W.A. Moore. 1940. Determination of BOD and dissolved oxygen in river mud suspensions. Ind. Eng. Chem., Anal. Ed. 12:711-714.

Sawyer, C.N. and P.L. McCarty. 1967. Chemistry for sanitary engineers. McGraw-Hill Book Co. 518 pp.

Seppänen, P. 1974. Lake aeration in Finland. Presentation at Conference on Lake Protection and Management, Madison, Wisconsin.

South Dakota Dept. of Environmental Protection. 1978. Report on non-point source pollution from selected watersheds throughout the state of South Dakota. January, 1978. 130 pp.

South Dakota Dept. of Game, Fish, and Parks. 1951-1979. Lake survey data, unpublished.

Speece, R.E. 1969. The use of pure oxygen in river and impoundment aeration. Presented at the 24th Ind. Waste Conf. May 6-8, 1969, Purdue University, Lafayette, Ind.

Speece, R.E. 1971. Hypolimnion aeration. J. Am. Water Works Assoc. 64(1):6-9.

Strickland, J.D.H. and T.R. Parsons. 1968. A practical handbook of sea water analysis. Fish. Res. Board Can., Ottawa. 311 pp.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Co., 743 pp.